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THE "PASCAL", A FAST DIGITAL ELECTRONIC COMPUTER FOR THE PHILIPS COMPUTING CENTRE

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One of the aims in the design of digital electronic computers is the attainment of higher and higher computing speeds. In view of the fact that Philips supply many components, such as valves, transistors, diodes and magnetic memory cores, to computer manufacturers, it was important to have first-hand experience as to the demands made on components for computers in this and other respects. Investigations on this subject go back to about 1954 when an experimental computer was built in the Philips Research Laboratories. This machine has also been used for mathematical work of the laboratories. On the basis of the experience thus obtained, two larger and faster machines have now been built, the PASCAL and the STEVIN. Both machines will be put to use in the Philips Computing Centre to test their utility in scientific and administrative problems taken from actual practice.

*This article gives a short description of the design and properties of the PASCAL, without going into the detailed circuitry. The article begins with an introduction to the field, outlining the general design of digital electronic computers and defining a number of concepts. For a fuller treatment the reader is referred to various textbooks on the subject **).*

A digital electronic computer can be used to solve problems of widely different kinds with great speed. In principle such machines can only perform the more elementary mathematical operations, such as addition, subtraction, multiplication, and division, and a number of simple organizational operations including, for example, discrimination (the act of distinguishing whether a number is larger or smaller than another). The problems to be solved can, however, frequently be reduced to a series of such elementary operations. These machines can thus be used to solve scientific problems involving integrals, higher-degree equations, ordinary and partial differential equations, matrices, etc., They have proved equally usefull in dealing with administrative problems in the field of pay-billing, stock administration, order and invoice processing. The possibilities have never been expressed more clearly than in the pronouncement of Lady Lovelace: "The machine can do whatever we know how to order it to perform" 1).

An experimental machine of this kind, which is suitable for the solution of scientific problems, has been built in the Philips Research Laboratories in Eindhoven. The machine has been given the name PASCAL, after Blaise Pascal who in 1642 constructed one of the first computers (which was of course mechanical). A second machine built in the laboratory and named after Simon Stevin, one of the fathers of accountancy, is intended more for administrative purposes. The STEVIN is basically similar to the PASCAL, but the auxiliary equipment has been extended in several respects so that it can be used for processing the large number of data that accompany administrative problems. Both machines, which belong to the class of "fast" machines, have been installed in the Philips Computing Centre (*fig. 1*), where the most important electronic computers used in the Dutch Philips factories have recently been brought together.

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*) Research Laboratories, Eindhoven.

**) See, for example, C. B. Tompkins, J. H. Wakelin and W. W. Stifler Jr., High-speed digital computing devices, McGraw-Hill, New York 1950; R. K. Richards, Digital computer components and circuits, Van Nostrand, New York 1957; G. Haas, Grundlagen und Bauelemente elektronischer Ziffernrechenmaschinen, Philips Technical Library, Centrex, Eindhoven 1961.
An elementary introduction to computers (including their historical development) is to be found in the book referred to in footnote 1).

1) B. V. Bowden, Faster than thought, Pitman, London 1953, pp. 30 and 398.

Fig. 2 gives a general view of the PASCAL. *Table I* contains a summary of the properties of this machine, in the nomenclature usual for electronic computers. In the course of this article these properties will be explained. On the assumption that this nomenclature is not familiar to most readers, a general survey of the components of a digital electronic computer will first be given, in which all the concepts and terms mentioned in Table I will be explained.

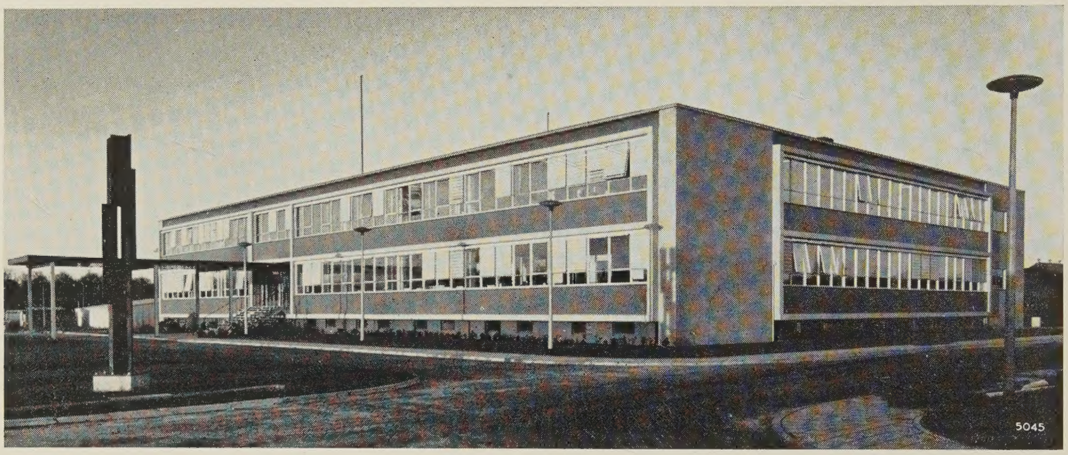

Fig. 1. The Philips Computing Centre in Eindhoven. In this building, which was officially opened on 21 March 1961, the principal electronic computers used by Philips in Eindhoven for administrative and scientific purposes have been collected. Apart from the PASCAL and the STEVIN it houses at present two IBM 650 digital computers, a Bull Gamma B digital machine and an analogue computer, the PACE.

The binary system

The description of the PASCAL in Table I begins with the word "binary", and therefore we start with a few remarks concerning the binary or two-digit system.

A digital machine calculates with discrete numbers, each number being expressed according to a certain code by a series of ciphers (digits). These digits are represented by elements or circuits that can take up several stable states. This is different from what happens in an analogue computer, in which a number is represented by a physical quantity that is continuously variable.

Most digital machines do not work with the decimal system but with the binary system. This system comprises only the digits 0 and 1 (called binary digits or "bits"), so that the numbers can be represented by means of a series of *bi*stable elements, such as flip-flops (circuits with two valves or transistors of which either the one or the other may be conducting) or magnetic cores (small ferromagnetic rings that can be magnetized in one of two opposite directions). Such a series of bistable elements, one for each bit, is called a *register*. It is of course quite true that there are also elements that can exist in ten stable states (e.g. the decade counter tube E 1 T [2]). Using such elements one would therefore also be able to work with the decimal system, but they require a much more complicated circuit, so that this system is hardly ever used in computers If some modern computers are yet said to work with the decimal system, this generally means that they make use of a system in which each decimal digit is itself separately coded by some means or other in binary form.

A disadvantage of the binary system is that the numbers are at least three times as long as in the decimal system. The advantages, however, amply counterbalance this disadvantage.

In the binary system the arithmetical rules are very simple:

$$0+0=0 \qquad 0+1=1 \qquad 1+0=1 \qquad 1+1=10$$

$$0\times0=0 \qquad 0\times1=0 \qquad 1\times0=0 \qquad 1\times1=1$$

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[2] A. J. W. M. van Overbeek, J. L. H. Jonker and K. Rodenhuis, A decade counter tube for high counting rates, Philips tech. Rev. 14, 313-326, 1952/53.

Table I. Principal data of the PASCAL, a binary parallel machine of the single-address type.

Word length	42 bits + 2 parity bits
Numbers with fixed point	41 bits + sign bit
Numbers with floating point	exponent (powers of 2): 7 bits + sign bit, fractional part: 33 bits + sign bit
Instructions	2 per word: 6 bits for the operation, 3 modification bits, 1 address interpretation bit, 11 address bits
Clock-pulse frequency	660 kc/s (basic period 1.5 μsec)
Some processing times *)	
addition and subtraction	with fixed point about 10 μsec with floating point 14-64 μsec
multiplication	with fixed point about 71 μsec with floating point about 59 μsec
division	with fixed point about 73 μsec with floating point about 61 μsec
number of instructions carried out per second in a typical programme	60 000
Memories (kinds and capacities)	
plug-board memory	16 words of 44 bits
modification memory	8 half-words of 22 bits
magnetic-core memory	2016 words of 44 bits
drum memory	16 384 words of 44 bits
magnetic tape	about 10^6 words of 44 bits with bits for longitudinal and transverse parity checks
Input (types and speeds)	
punched tape (5 or 8 channels)	120 characters per second with the possibility of stopping at each character; or 1200 characters per second, with continuous reading and using a special character for stopping
punched cards	$2\frac{1}{2}$ or 12 cards per second (both "Bull" and "IBM" code)
magnetic tape	on average 8000 words per second ("Ampex")
Output (types and speeds)	
punched tape	60 characters per second ("Teletype")
punched cards	$1\frac{1}{4}$ cards per second ("Bull" tabulating machine)
magnetic tape	8000 words per second ("Ampex")
electric typewriter	10 characters per second ("IBM")
line printer	$2\frac{1}{2}$ lines of 90 characters per second ("Bull" tabulating machine)

*) Including waiting time for fetching the number and the instruction from the memory.

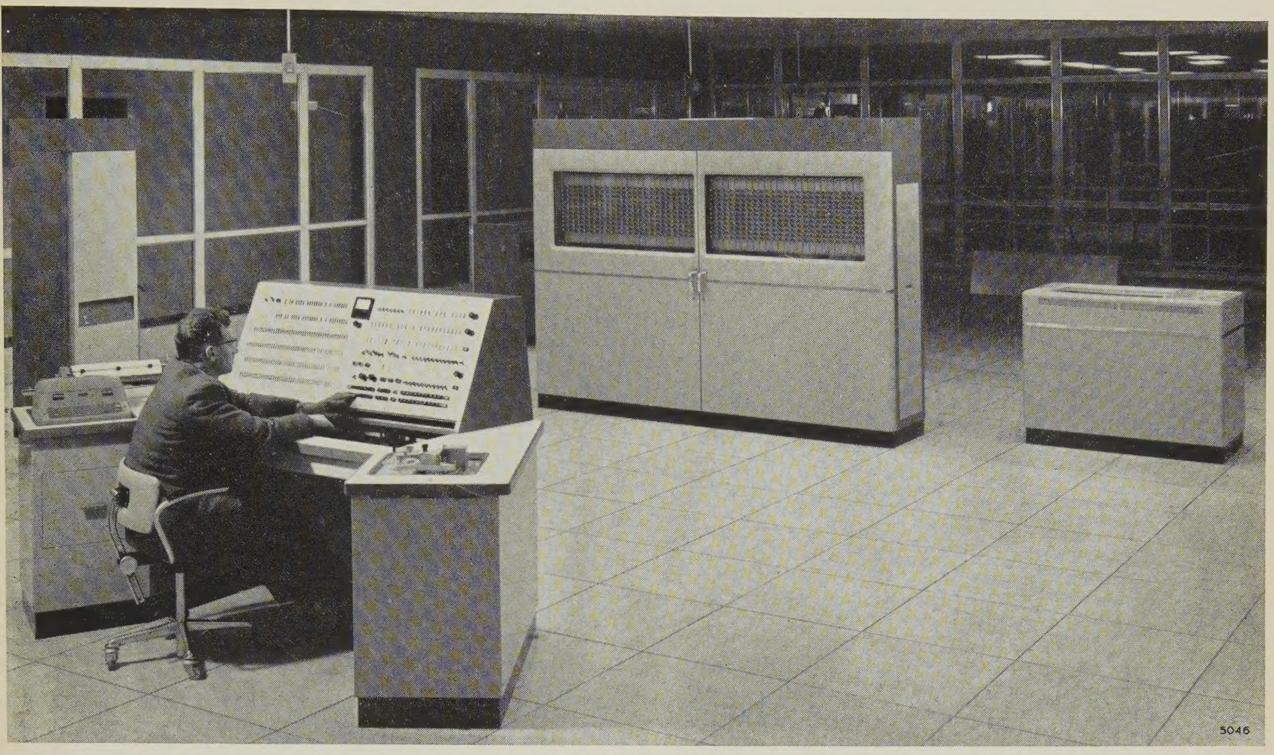

Fig. 2. General view of part of the PASCAL equipment. The large cabinet contains the principal components of the computer, viz. the arithmetical unit, the control unit and the magnetic-core memory. The low cabinet on the right contains the magnetic-drum memory. The PASCAL is operated from the desk in the foreground. The following are not visible: the magnetic tape recorders of the memory, the punch-card equipment for input and output, and the line printer.

We will give a simple example of the use of the binary system. In the decimal system the number 13.625 has the value of $1\times 10^1 + 3\times 10^0 + 6\times 10^{-1} + 2\times 10^{-2} + 5\times 10^{-3}$. In the binary system this number becomes 1101.101, as the value of this is $1\times 2^3 + 1\times 2^2 + 0\times 2^1 + 1\times 2^0 + 1\times 2^{-1} + 0\times 2^{-2} + 1\times 2^{-3}$ which, expressed in the decimal system, is equal to 13.625.

Here are a few calculations in the binary system:

$$\begin{array}{rr} 110110011 = & 435 \\ +111001 = & +57 \\ \hline 111101100 = & 492 \end{array} \qquad \begin{array}{rr} 1110010 = & 114 \\ -1011 = & -11 \\ \hline 1100111 = & 103 \end{array} \qquad \begin{array}{rr} 1101 = & 13 \\ \times 1011 = & \times 11 \\ \hline 1101 & \\ 11010 & \\ 1101000 & \\ \hline 10001111 = & 143 \end{array}$$

Survey of the components of a digital computer

Practically every digital computer consists of the following components:

1) An arithmetical unit, in which the operations of addition, subtraction, multiplication and division, and a few others, can be carried out.
2) A memory, in which the data that have to be used or stored during the computation are kept. The memory consists of registers, each of which is indicated by a number, the *address*. The contents of a memory register are called a *word*. This may be a *number*, or an *instruction* expressed (coded) in a certain way as a binary number.

   An instruction indicates what operation is to be carried out. There must also be an indication concerning the number or numbers on which the operation is to be performed. In this article we shall only discuss computers having instructions of the single-address type, such as those used in the PASCAL. Here each instruction gives the address of *one* number. Provision has to be made for the second number that is normally concerned in a process to be already available in the arithmetical unit, either as a result of the previous process or as the result of a special instruction.
3) A control unit, whose function it is to ensure that the separate instructions are carried out in the correct sequence. The complete list of instructions to be carried out during the desired computations, the *programme*, is stored in the memory.
4) Input and output devices. The programme, and the numbers belonging to it, are supplied to the machine by means of an input device, e.g. a

punched-tape or a punched-card reader. To extract the answers from the machine, there is an output device, e.g. an electric printer or a card punch.

The arithmetical unit

The arithmetical unit of most machines contains three registers (see *fig. 3*), which may each consist of a row of flip-flops. The register *M* forms the connection with the memory. If a number is brought from the memory to the arithmetical unit, the memory supplies the requisite voltage pulses to set the flip-flops of *M* in the corresponding states. The successive digits of the number can be transported either one by one (serial transport) or simultaneously (parallel transport). The latter requires more equipment but less time and is therefore used in the PASCAL. All numbers must also pass through *M* on their way *to* the memory.

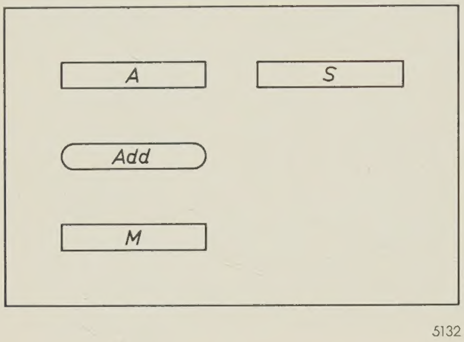

Fig. 3. Diagram of the arithmetical unit of a digital computer. The register *M* contains the number brought from the memory. The adder *Add* gives the sum of the number in *M* and the number in the register *A* (the accumulator). (This may, for example, be the result of a previous operation.) The register *S* (shift register) is used in multiplication and division. Each of the registers *A*, *M* and *S* consists of a series of flip-flops (42 in the PASCAL).

The second register of the arithmetical unit is the *accumulator A*, so called because the sum can be accumulated therein during addition. The third register *S* (*shift register*) is used in multiplication and division, among other things.

The central part of the arithmetical unit is the *adder Add*. The adder forms the sum of the numbers standing in *A* and *M*. This is a fundamental operation, and the circuits by which it is carried out (and which are built up from "logical" circuits) will presently be discussed in more detail. During addition the sum thus formed is generally taken up in *A*, and the previous contents of this register are lost.

The adder *Add* may be designed to add the numbers in *A* and *M* digit by digit, or it may contain a specific circuit for each digit, so that all digits of the numbers are processed at the same time. In the former case one speaks of a serial adder, in the latter of a parallel adder. Analogous to what was said about transport, the parallel adder requires a more complicated circuit but works much more rapidly than the serial adder.

Subtraction does not differ much from addition: the number arriving at *M* from the memory is there first given the opposite sign (most digital computers are designed so that this can be done quite simply by changing ones into noughts and vice versa; this is known as inversion) and then added to the number standing in *A*.

In a multiplication the multiplier is first placed in *S* by a separate instruction. The register *A* is "cleared" by the multiplication instruction proper (if there is a number in *A* that has to be kept, this number must first be transferred to the memory by a suitable instruction) and the multiplicand is brought to *M*. The multiplication process now takes place as follows:

a) If the last (least significant) figure in *S* is a 1, the contents of *M* are added to *A*, after which *A* and *S* are both shifted one place to the right. During this shift the last figure of the multiplier, which has now performed its task, is lost. The last figure from *A*, which must not become lost as it is part of the product, is inserted in the now empty first position of *S*. The first position in *A*, being now free, is filled with a zero (it being assumed that in this and the following example the numbers are positive; cf. the example in *fig. 4* which represents the various stages in the multiplication of $11 \times 13 = 143$, for registers of 5 bits).

b) If the last figure of *S* is 0, nothing is added, but the contents of *A* and *S* are still shifted one place to the right.

Because of the shift, both in case *a*) and in case *b*), the multiplier digit to be considered always stands in the last position of *S*. The adding and/or shifting is repeated until the multiplication is finished; the whole multiplier will then have been shifted out of *S* and the product (which will now have twice the length of a register) will occupy the registers *A* and *S* together.

Division proceeds analogously but in the opposite direction to multiplication. Here the dividend must first be placed in the *A* register by means of a separate instruction. (*S* may also contain a part of the dividend if the latter happens to consist of more digits than normal.) The division instruction proper then places the divisor in *M*. The arithmetical unit contains a circuit that first "compares" the contents of A and M. The contents of M are now subtracted from the content of A if possible, and a 1 is placed at the right-hand end of S if subtraction takes place. The contents of A and S are then shifted together one place to the left. If it appears that the subtraction is not possible, only a shift takes place, and a 0 is placed at the right-hand end of the S register. At the end of the process the quotient will be in S and the remainder in A.

The procedure followed in carrying out such a composite instruction is called a microprogramme.

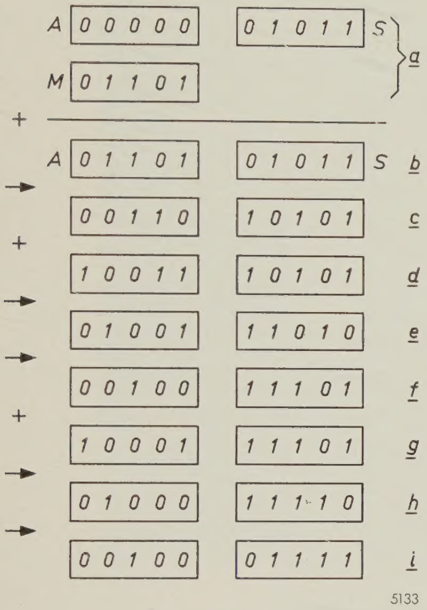

Fig. 4. Example of a multiplication in the arithmetical unit: the multiplication 1011 × 1101. *a*) Initial state of the registers A, S and M. *b*) - *i*) State of the registers A and S during the successive steps of the multiplication. The last figure in S always indicates what the following step has to be. If there is a 1, the contents of M are added to those of A (see *b*, *d* and *g*), after which the contents of A and S are together shifted one place to the right (see *c*, *e* and *h*). If there is a 0, only shifting takes place (see *f* and *i*). At the end of the operation the product (twice the register length) is found in A and S together.

The memory

The memory of an electronic computer must comply with two conditions: it must be large, i.e. it must be able to contain many words, and it must be rapid, i.e. the selection and reading of a word must not take long. As these conditions are more or less incompatible, most machines have several kinds of memories, which comply with either the one or the other demand.

In practice one frequently meets a magnetic-core memory as a rapid memory (*fig. 5*) and a magnetic drum memory (*fig. 6*) as a large (but slow) memory. The magnetic core memory then works in direct combination with the arithmetical unit and is called the working memory, while the drum memory contains the information that is not directly concerned in the computing process. Both kinds of memory have been described previously in this journal [3]).

The instructions

As already mentioned, an instruction indicates which operation is to be carried out and where in the memory the relevant number is to be found. One might imagine a list of all admissible operations, so that each one could be indicated by its number in the list. In this way each instruction takes the form of:

number of the operation	address of the number

Some find it easier to indicate an operation with a readily remembered group of letters. This can, if necessary, be translated by the machine itself into the numerical code during the input of the problem. For example, *TOA* 513 might mean: add to A the number found at address 513. The number enters the arithmetical organ via register M and is added to whatever there was already in A. This sum can, for example, then be stored at address 127 by the instruction: *SAP* 127 (store A positive at address 127). In a multiplication it is first necessary to set up the multiplier in S by an instruction, e.g. *LDS* 500 (load S with the number at address 500). The microprogramme of the multiplication is then started by means of the instruction *MPY* 501 (multiply the number at address 501 by the number in S).

The instructions are stored in a row of successive addresses in the memory. When an instruction has been carried out, the control unit (cf. the following section) normally fetches the new instruction from the next address. If one wishes to go over to another row of instructions, "jump" instructions are used. On the instruction, for example, *JUN* 203 (jump unconditionally to address 203), no processing takes place but the control fetches the next instruction from address 203 and then proceeds to address 204 and subsequent ones. Such a jump may also be "conditional", i.e. it is carried out only if a certain condition is fulfilled. Thus, for example, the instruction *JAP* 200 means: jump, if

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[3]) H. J. Heijn and N. C. de Troye, A fast method of reading magnetic-core memories, Philips tech. Rev. **20**, 193-207, 1958/59.

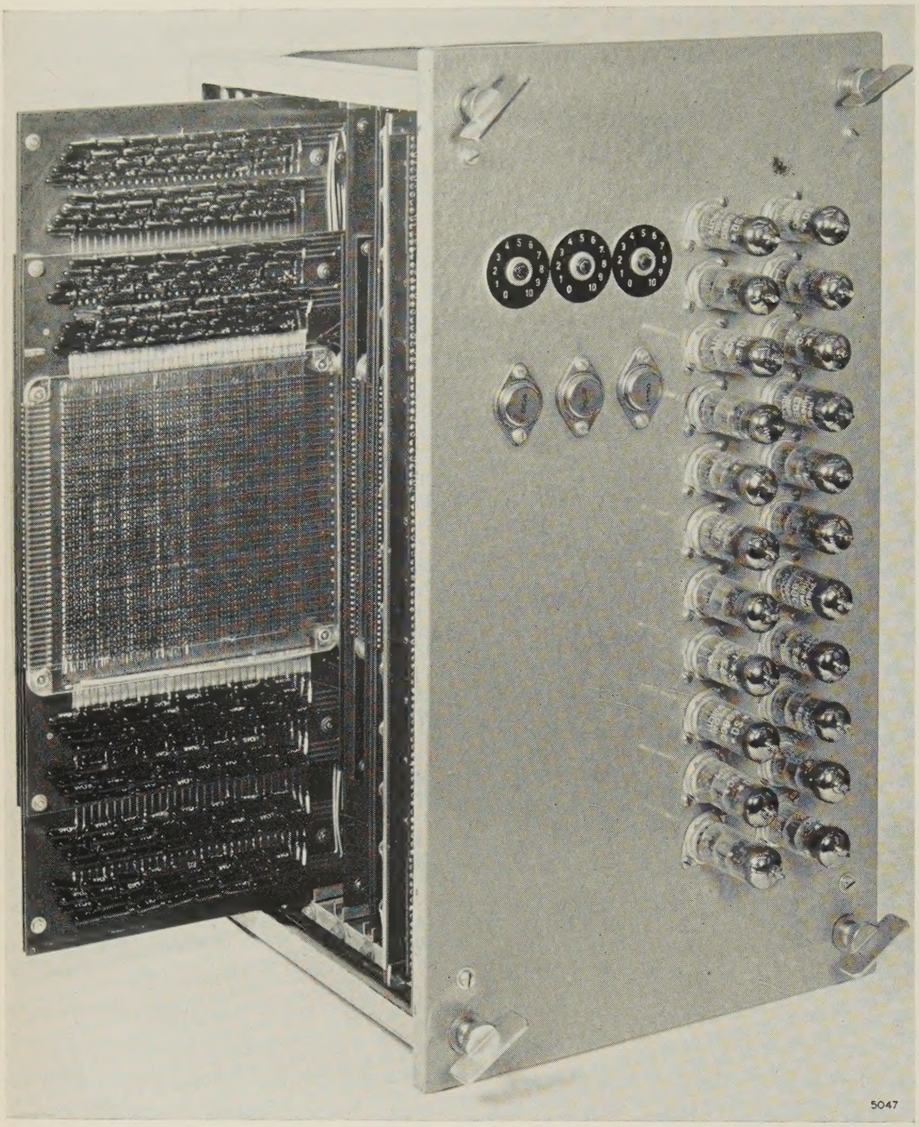

Fig. 5. A magnetic-core memory. This memory consists of four panels, each containing 256×44 cores for 256 words. One panel has been pulled out from the chassis. Printed wiring is used; the connections between the panels take the form of connection strips that engage in contact clamps. The chassis also contains circuits that serve for writing data into the memory and for reading them out of it. The PASCAL contains two of these memories.

the accumulator A is positive, to address 200. If the contents of A are negative, this jump is not carried out and the programme continues normally.

A number of instructions in the PASCAL which differ from the conventional ones will presently be discussed in more detail.

The control unit

The overall working of a digital computer proceeds in two phases. In the "control phase" an instruction, consisting of an operation part and an address part, is brought from the memory to the control unit and there placed in a register, the C register. A selection circuit connected to the C register selects the microprogramme indicated by the operation part of the instruction, while the address part of the instruction is transported to a second register of the control unit, the address-selection register T. There is a further selection circuit connected to this register; this selects the word to be processed from the appropriate address in the memory. At the instant that the address part of the instruction is transferred to T, the latter still contains the address of the instruction in the process of being carried out, and this address must not be lost. (It should be remembered that each instruction *has* an address where it is to be found, and *contains* the address of the number to be processed.) It is therefore temporarily placed in a suitable place of safety. After this the number specified by the instruction may be taken from the memory and brought to the arithmetical unit.

Then the control changes over to the "operation phase", and the microprogramme for the corresponding operation is started. Once this is completed, the machine switches back to the control phase. The address of the instruction just completed is brought out from its place of safety and, increased by one, brought back to T, so that this register now contains the address whence the new instruction has to be fetched. The cycle can then start again.

When a jump instruction (in which as already mentioned no processing takes place) occurs, the number in T is replaced by the address mentioned in the instruction, so that the following instruction is fetched from this place, the operation phase being simply omitted.

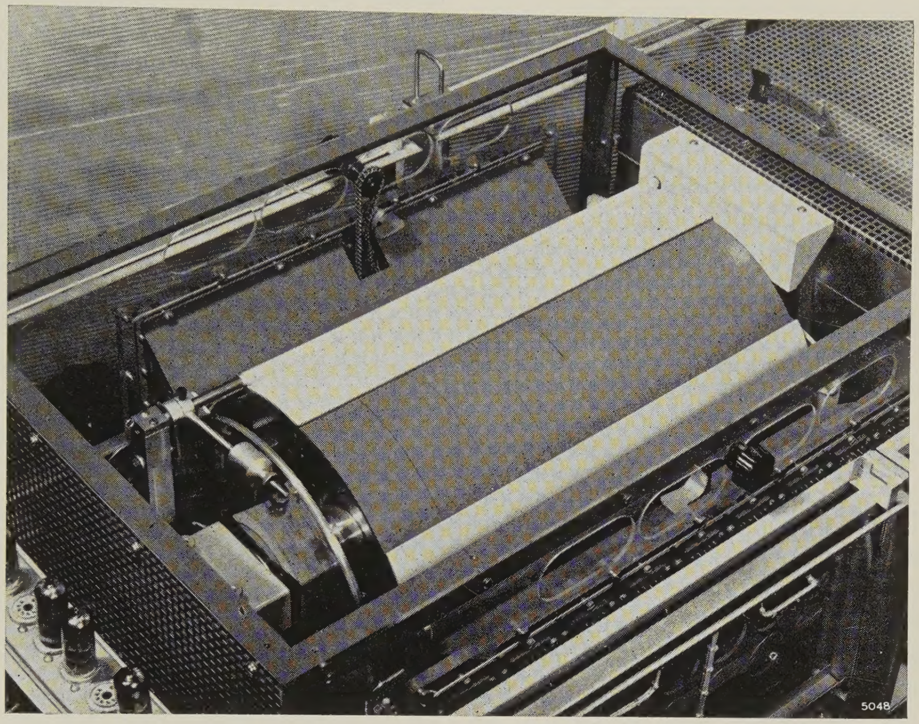

Fig. 6. A drum memory. The continuously rotating drum, which is coated with a thin layer of magnetizable material, is driven by an electric motor. During rotation, the drum passes under a series of heads that magnetize small areas of the surface in one of two opposite directions and that are also used for reading the magnetization. The drum here illustrated is used for the PASCAL; it rotates with a speed of 6000 rev/min. It has 256 heads which are arranged in two horizontal rows along the drum. Some connections to those of the front row are visible. The white metal plates ensure that the heads do not touch the drum when it expands. For this purpose the plates are pivoted and float on the air stream produced by the rotating drum. As the drum expands, the plates are raised a little further and the angular displacement thus produced increases the distance between the heads and the shaft of the drum.

Input and output devices

For the input of programmes and numbers, use can be made of punched tape, punched cards or magnetic tape. On these the information need not be placed in the binary form required by the machine but may, for the convenience of the user, take a decimal form or the above-mentioned letter code. For punched tape one can, for example, make use of the teleprinter code.

The machine is fed with a so-called input programme with which this code is translated into the binary form. The mechanical input devices work much more slowly than the machine can perform the translation, so there is plenty of time for this translation work.

Similarly, an output programme arranges for the answers to be given to the output devices, which may take the form of, for example, an electric typewriter, a tape punch, a line printer, a card punch or a magnetic-tape apparatus.

Logical circuits

To make clear the character of logical circuits, we might perhaps best consider the addition circuit, *Add* in fig. 3. Let us consider the situation somewhere in the middle of the number. We have to add the digit a from A to the digit m from M, and we may have to carry one from the previous digit, which may be regarded as the addition of a further digit c_i. The result is the digit s, and c_u to be carried to the next digit.

Table II gives the possible combinations of a, m and c_i that may occur, and the corresponding values of s and c_u. It can be seen that, for example, $c_u = 1$ if:

$a = 1$ and $m = 1$,
or: $a = 1$ and $c_i = 1$,
or: $m = 1$ and $c_i = 1$,
or: $a = 1$, $m = 1$ and $c_i = 1$.

Table II. The sum s and the outgoing carry c_u at a certain position in the adder, for different values of the digits a and m to be added and the incoming carry c_i.

a	m	c_i	s	c_u
0	0	0	0	0
1	0	0	1	0
0	1	0	1	0
0	0	1	1	0
1	1	0	0	1
1	0	1	0	1
0	1	1	0	1
1	1	1	1	1

Now we may represent a 0 by e.g. a low voltage and a 1 by a high voltage (for example 10 volts and 15 volts). A circuit can then be constructed with diodes and resistors which, when supplied with voltages corresponding to the values of a, m and c_i, only supplies a high output voltage if the above conditions are complied with. This circuit thus gives the required result c_u.

One may also say that the circuit carries out the operations *and* and *or* occurring in the conditions. These are operations from a branch of mathematics called propositional logic, hence the name "logical circuits".

Logical circuits are built up from two basic types corresponding to the two fundamental operations, viz. the *and* and the *or* circuit. *Fig. 7a* represents the *and* circuit. Point P has the high voltage. The output, point U, will now have the high voltage only if both the points x *and* y have the high voltage. This circuit will thus give 1 only if x *and* y are each equal to 1. In the *or* circuit, fig. 7*b*, point Q has the low voltage. The point U will have the high voltage if either x *or* y *or* both have the high voltage. This circuit thus gives a 1 if x *or* y *or* both are equal to 1.

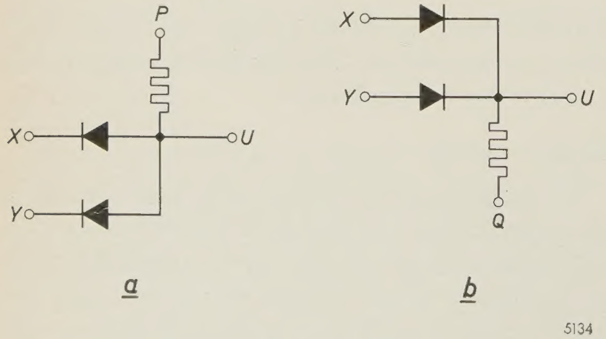

Fig. 7. The two basic types of logical circuits. *a*) *and* circuit. Point P here has a "high" voltage. Point U only has a high voltage if both x and y have a high voltage. *b*) *or* circuit. Q here has a "low" voltage. Point U has a high voltage if x or y or both have a high voltage.

The circuit for obtaining c_u from a, m and c_i might be as shown in *fig. 8*. To reduce the delaying effect of parasitic capacitances in the circuit, the voltage V is chosen larger than the voltages a, m and c_i.

One of the functions of logical circuits in computers is to activate a certain part of the machine on the receipt of certain combinations of input signals. This is the case for example in the above-mentioned selection circuit connected to the operation part of the C register in the control unit which switches on the correct microprogramme, and in the selection circuit of the T register which brings about the reading of the desired address in the memory.

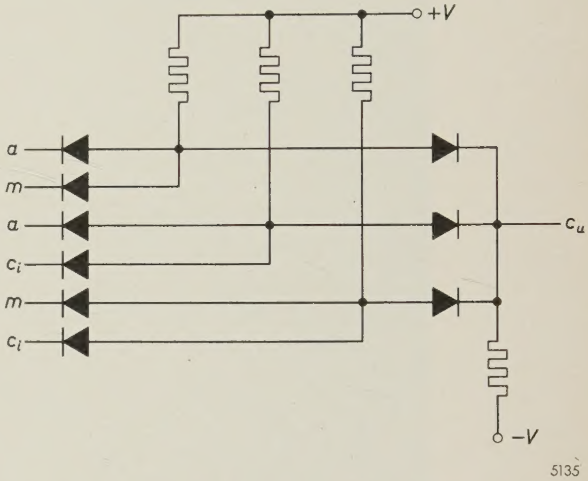

Fig. 8. Example of a logical circuit which determines the carry c_u to the following digit from the incoming carry c_i and the digits a and m at a given position in the registers A and M (for example: 0 is represented by a low voltage of 10 V and 1 by a high voltage of 15 V). This circuit is composed of three *and* circuits and one *or* circuit. (The adder of the PASCAL uses a different circuit for a more rapid determination of the carry.)

Special features of the PASCAL

So much for the general description of the working of digital electronic computers. In the following section of this article we shall discuss a few special features in the equipment of the PASCAL, and we shall follow more or less the same arrangement as used in the first section. We shall here deal with some more new concepts, such as the subroutine, the number coding with floating point, and the modification of an instruction.

The PASCAL shares many of its special features with other machines of recent years; this will not be mentioned every time. As far as we know, the following have not yet been used in other machines: the method for rapid transfer of instructions in the addition circuit; the Σ switch; the plug-board memory; the method of modifying instructions; the link instructions for going over to a subroutine, and a few more special instructions.

At the end of the article we shall discuss a few constructional problems and make some remarks concerning the PASCAL in comparison with other machines.

The coding of the numbers

The binary notation for numbers was discussed in the beginning of this article. It is obvious that when numbers expressed in this notation are added or subtracted, all the numbers must have the decimal point, or rather the "binary point", in the same place. This is referred to as *fixed-point notation.* The possible magnitude of numbers expressed in this notation is limited. It was mentioned in Table I that 41 bits are available for fixed-point numbers in the PASCAL. In order to distinguish positive and negative, one bit (sign bit) is added, 0 being used to indicate a positive and 1 a negative number. Now if the point is, for example, placed at the end of the number, the range covered by 41 bits extends from 0 to about 10^{12} (12 decimals). This range can be increased considerably by using the *floating-point* notation, in which numbers are indicated by a fractional part p and an exponent q. The value of such a number in the binary system is then $p \times 2^q$, the absolute value of p always being chosen to lie between a half and one, so that q really indicates the position of the point. In the PASCAL the $41 + 1$ available bits are divided into a fractional part of 34 bits, one of which is a sign bit, and an exponent of 8 bits, one of which is a sign bit. The absolute value of the numbers can now lie between $\frac{1}{2} \times 2^{-127}$ and $1 \times 2^{+127}$, or in other words between about 10^{-38} and 10^{+38}. The accuracy (33 bits in place of 41) is of course smaller than in the fixed-point notation and will cover about 10 decimals.

Addition and subtraction of numbers expressed in the floating-point notation is more complicated and takes longer than for numbers in the fixed-point notation, because the exponents of both numbers must first be compared and made equal, while an extra step may be necessary after addition in order to bring the absolute value of the fractional parts back to between $\frac{1}{2}$ and 1. Multiplications and divisions are a little faster, mainly because the length of number (fractional part) to be processed is shorter (see Table I). There are special microprogrammes in the control unit for working with numbers in the floating-point notation.

The arithmetical unit of the PASCAL

The arithmetical unit of the PASCAL has the three registers M, A and S discussed above. The registers M and A serve as inputs for the adder, which is a parallel one. Only 0.8 μsec after the arrival of the numbers in the registers, the answer will be available at the output of the adder. Special measures were obviously required to attain such a short addition time. Thus the carries were not only transferred digit by digit for all 41 digits, but also determined for successive blocks of 7 digits at once and passed on to the following block. In this way it was found possible to gain time without having to use too many extra components.

The determination of a carry takes 40 nanoseconds for each digit. A separate logical circuit determines the carry for a block of 7 digits to the first digit of the next block, from the incoming carry and the state of the registers A and M for these digits. This takes 100 nsec. In the second block the passing on of the carries and the determination of the carry of the third block can already start while the carry from the third to the fourth digit in the first block has still to be determined. The last carry of the addition is obtained after 780 nsec in this way, while without these block carries it would take $42 \times 40 = 1680$ nsec.

This method of working also affords a check on the operation of the computer, because at the end of each block the carry is produced in two ways: first with the separate logical circuit, and immediately afterwards by virtue of the fact that the carries in the block are determined digit by digit. If these two carries do not agree, an error has occurred and the machine is automatically stopped.

A complete addition, including the fetching of the instruction as well as of the number, admittedly takes much longer than the above-mentioned addition time of 0.8 μsec (in the PASCAL it takes on the average 10 μsec), but the very short intrinsic addition (or subtraction) time is still of prime importance, particularly for division. Division is after all made up of a number of subtractions, and furthermore the course of the process differs according as subtraction is or is not possible, so that the microprogramme of the division must still decide for each subtraction how to continue. Thanks to the very short addition time each division step in the PASCAL still does not occupy more than $1\frac{1}{2}$ μsec.

The clock pulses

The above-mentioned time of $1\frac{1}{2}$ μsec is called the basic period of the machine, and all separate steps in the working of the machine occur at intervals of $1\frac{1}{2}$ μsec or multiples of this. These intervals are determined by a periodic series of voltage pulses, the clock pulses, which are formed by means of a disc fixed to the shaft of the drum memory. The circumference of the disc is provided with small teeth of a permanently magnetic material. As the disc rotates, the teeth generate an AC voltage in a reading head, from which the pulses are taken. They have a frequency of 660 kc/s and thus appear at intervals of about $1\frac{1}{2}$ µsec.

To illustrate the function of the clock pulses in the working of the PASCAL, let us consider a logical circuit. This provides, as mentioned above, a high or a low output voltage, depending on whether or not a certain combination of input signals is present. This output voltage nearly always serves for setting a flip-flop to a corresponding state. This must often be done for several flip-flops simultaneously. The output voltages of the different logical circuits are not, however, usually available at precisely the same instant (this depends on, for example, the size of the circuits). The instants at which the flip-flops are activated must not therefore be determined by these output voltages. The moment of activation of each flip-flop is therefore determined by the first clock pulse appearing after the output voltage of the logical circuit concerned has been formed. This happens as follows.

The flip-flop F (*fig. 9*) is not activated by the output voltage of the logical circuit L but by the clock pulse k; the output voltage of L does however determine which half of the flip-flop is to be supplied with the clock pulse, by means of the two-way switch P. Two voltages of opposite sign are needed to operate the two-way switch, i.e. the polarity of these voltages determines the state of P. The voltages are formed by the circuit N and their polarity is determined by whether the output voltage of L is high or low. Two cathode followers K connected to the flip-flop supply the power for activating other parts of the machine. The circuit of fig. 9 is a basic circuit which occurs in many different parts of the machine.

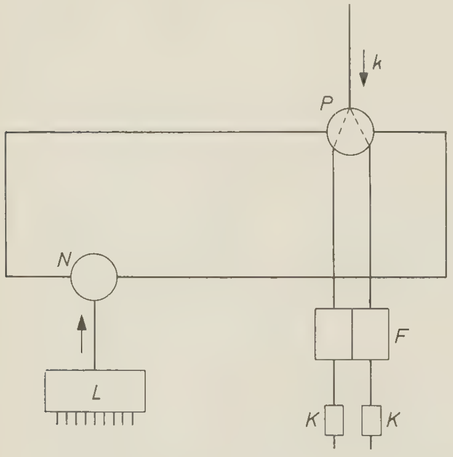

Fig. 9. Basic circuit used in many parts of the PASCAL. This kind of circuit is used to set a flip-flop to a state determined by the output voltage of a logical circuit at the instant when a clock pulse appears. The logical circuit L supplies either a high or a low voltage. On receipt of this, the circuit N produces a positive and a negative voltage, the polarity of which is determined by the magnitude of the signal from L. The state of the two-way switch P is in its turn determined by the polarity of the voltages from N. The first subsequent clock pulse k is now passed by this switch to one of the two halves of the flip-flop F. Depending on the magnitude of the voltage supplied by L, this flip-flop will thus take up a certain position. Cathode followers K connected to F supply the power for activating other parts of the machine.

The basic period of $1\frac{1}{2}$ µsec has been chosen so that all logical circuits will have supplied their output signal within this period.

The Σ switch

The outputs of the adder are connected to a six-way electronic switch Σ. This makes it possible to transfer the sum obtained in the adder to one of a number of other registers (see *fig. 10*). The Σ switch actually consists of 42 identical switches, because it must be possible to effect the six connections for each digit simultaneously. First of all the sum can be placed in A; this is necessary in normal addition instructions. The sum can also be placed in A shifted one place to the left or right, so that shifting during division or multiplication does not cost any additional time. Because of this little trick the PASCAL requires an average of only 71 µsec for a multiplication (including fetching the instruction and the multiplicand), and 73 µsec on average for a division.

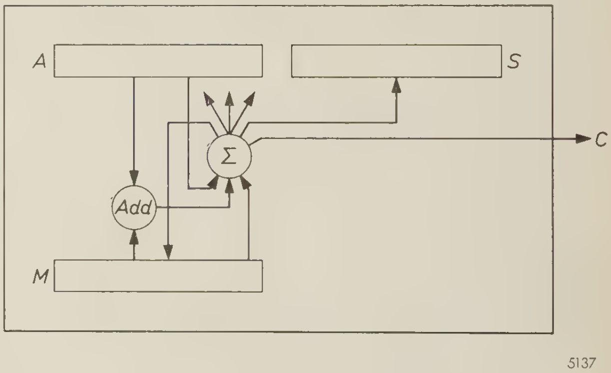

Fig. 10. Diagram of the arithmetical unit of the PASCAL with the 6-way Σ switch. The latter is able to make the requisite connections (42 in parallel, one for each digit) between the adder *Add*, the registers A, M and S of the arithmetical unit and register C of the control unit.

The Σ switch also makes it possible to transport the sum obtained in the adder to the S register, which can thus be used also as an accumulator, and to the M register, so that the sum can be written directly in the memory. An arbitrary memory address can therefore also serve as an accumulator.

Finally, Σ can transport the sum to the control unit. This is used in modifying the instructions. (This important facility of the PASCAL will be discussed below.)

It is also possible to transfer the contents of register A or of register M to the six above-mentioned locations. These possibilities are used in a number of instructions in certain phases of the control.

To give an idea of the speed of the PASCAL, we may mention that it processes about 60 000 instructions per second for a programme containing one long operation (multiplication or division) for every ten short ones (addition, subtraction, etc.).

The memories of the PASCAL

As already mentioned, most computers have a rapid working memory and a large, slow, secondary memory.

The PASCAL has in all five kinds of memory. The working memory is of the magnetic-core type. The most important slow memory is a magnetic drum. There is also a very large slow memory with magnetic tape and two small special memories: a "plug-board memory" and a "modification memory".

a) The magnetic-core memory can accommodate 2016 words. The address part of an instruction consists of 11 bits, with which a selection can be made from $2^{11} = 2048$ addresses. The 32 addresses that do not occur in the magnetic-core memory are used for the special memories and for a few registers, among others A and S of the arithmetical unit. Selection of a certain address and reading of the contents requires 3 μsec in this memory, re-writing after reading a further 3 μsec.

b) The drum memory can contain 16 384 words, divided into "blocks" of 128 words. A block is written on two tracks that can each contain 128 half-words and which are written and read simultaneously, each with its own head. Writing erases whatever registration was already present. The access time with a drum memory (i.e. the time required for the selection of a certain word and the reading of it) is in principle variable, as a word can only be read when the relevant part of the rotating drum passes under the head of this track. In the PASCAL this variable access time causes no difficulties, as a block of words is always transferred in its entirety from the drum to the magnetic-core memory (which is divided into blocks of 128 words for this reason). As soon as the control receives a transport instruction, transport starts immediately and is maintained for a complete revolution of the drum. Provision is made for placing the words in the positions in the magnetic-core memory corresponding to their correct positions in the block, even if reading is started in the middle of a block. During such a transport of a block from the drum to the magnetic-core memory, transport of another block may take place in the reverse direction. One revolution of the drum takes 10 msec, so the transport speed is 12.8 words per msec in each direction.

During such transport the PASCAL continues to compute, albeit sometimes at slightly reduced speed (the reduction amounts at the most to 15%; it would take us too far afield to go into this in more detail).

c) The magnetic tape serves as a much bigger but much slower memory. It is possible to store some 10^6 words on each roll of magnetic tape. Here again exchange of data with the magnetic-core memory takes place in blocks of 128 words and, if more than one magnetic-tape apparatus is used, is possible in two directions simultaneously. A number of magnetic-tape units can be seen in *fig. 11*.

d) The plug-board memory can contain 16 words, which are inserted by placing plugs in appropriate holes; these 16 registers bear the addresses 0-15, which do not occur in the magnetic-core memory (see above). The plug-board memory serves for the storing of parameters that should be easy to change during computation, for the insertion of small test programmes, and for the starting of a new programme. To make this last even easier, the register with address 0 is equipped with push-buttons instead of plugs. The plug-board memory and the push-buttons for address 0 are to be found on the control desk (see fig. 11).

e) The modification memory contains eight half-words (i.e. space for eight instructions, see below). Transistorized flip-flop registers are used for the storage. This makes for a very short access time, just as in the plug-board memory. The registers can be filled in the same way as those of the magnetic-core memory by using normal instructions. They are given the addresses 16-23. The use of the modification memory will shortly be described in more detail.

After the discussion of the arithmetical unit and the memory we ought now to look more closely at the control of the PASCAL. It is, however, necessary first to consider anew the coding of the instructions.

The coding of instructions in the PASCAL

The chosen word length of 42 bits is determined mainly by the desired computing accuracy. The instructions are, however, very much shorter. Each word can then contain two instructions that are processed by the control successively. They are indicated as I_1 and I_2.

For each instruction 21 bits will now be available. 6 of these serve to indicate the kind of operation,

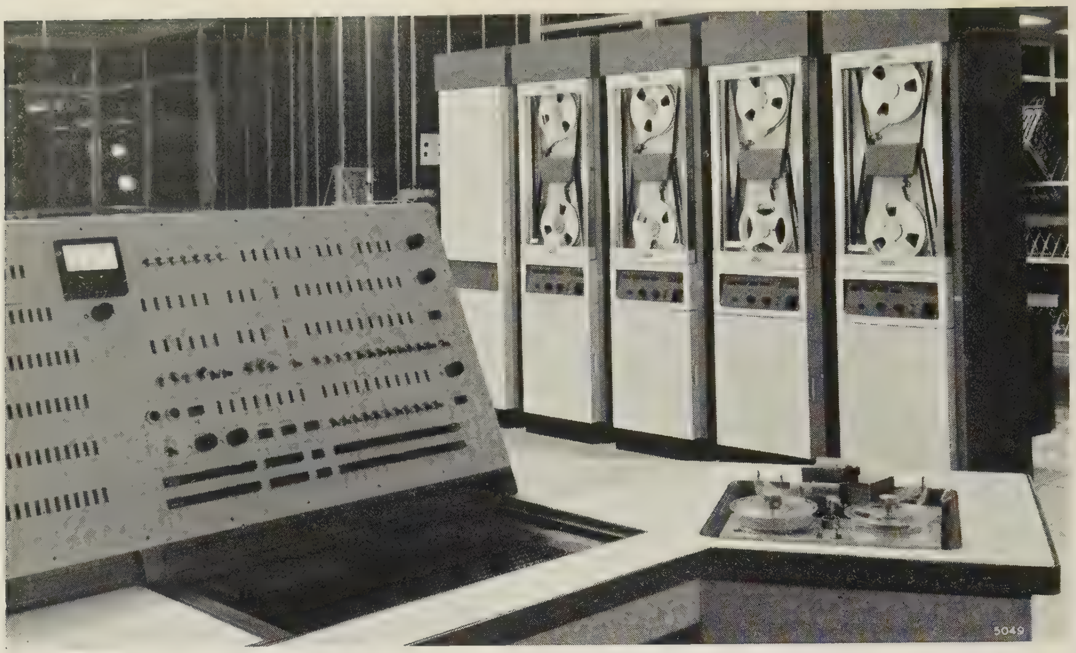

Fig. 11. Part of the control desk. At the back are some tape units which are used as a large, slow memory. The plug-board memory can be vaguely seen on top of the desk while the push-button register for address 0 is at the bottom right-hand side of the panel. To the right on the desk there is the reader for the input of programmes recorded on punched tape.

so that $2^6 = 64$ different operations can be carried out. As we have already seen, 11 bits are required for the address of the number to be processed (for a total of $2^{11} = 2048$ addresses in the various memories). Of the 4 remaining bits of an instruction, 3 are used for selecting one of the 8 modification registers; for an instruction can still be modified even after having been fetched from the memory but before being executed. By making use of the possibility of modifying instructions it is sometimes possible to achieve great economies in time and in memory space in the case of programmes in which a certain series of instructions has to be repeated a number of times. This will be made clearer below in the section in small print.

In the PASCAL a distinction is made between modifications in a register with an even number, and those in a register with an odd number. Since a magnetic-core memory has the property that a word is erased from the memory when it is read, such a word must be re-written in the memory. If the word that is read and brought to the arithmetical unit is an instruction pair, such re-writing is postponed till after the modification of the instruction. While the modification is being added to the instruction in the arithmetical unit, both the original and the modified form of the instruction are present in the arithmetical unit, so that it is possible to choose which one is to be re-written in the memory. When an even modification register is involved, the unmodified instruction is re-written, while with the odd registers the modified one is taken.

Of the 21 bits there now still remains 1 bit, the so-called address-interpretation bit. This determines how the address part of the instruction has to be interpreted. In normal cases this bit is a 0. If, however, it is a 1, then the address part of the instruction is not considered as an address of a number but as the number itself. This possibility can be utilized if some operation has to be carried out on a positive number < 2048. No separate memory position will then be required, for the operand is already given as part of the instruction.

The form of a complete instruction is represented in *fig. 12*.

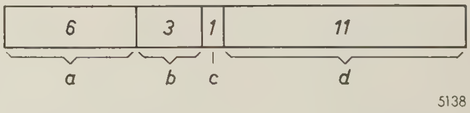

Fig. 12. Distribution of the 21 bits of an instruction: *a*) 6 bits indicate the operation to be carried out; *b*) 3 bits indicate the required register in the modification memory; *c*) one bit serves for the address interpretation; *d*) 11 bits indicate, if there is a 0 in (*c*), the address in the memory of the number to be processed. If in (*c*) there is a 1, the contents of (*d*) are to be taken as the number to be processed.

As an example of the application of a modified instruction, let us consider the calculation of the scalar product of two vectors **a** and **b** having ten components: $\mathbf{a} \cdot \mathbf{b} = a_1b_1 + a_2b_2 + \ldots + a_{10}b_{10}$. The components $a_1 \ldots a_{10}$ and $b_1 \ldots b_{10}$ are placed in the memory at addresses $n \ldots n+9$ and $n+10 \ldots n+19$. Now here is a process recurring ten times: multiply

a_i by b_i, add this to the previous result that might, for example, be located at address m, and store the new result again at address m. This requires the following instructions, whose meanings have already been indicated on p. 5 (they are placed at addresses k, $k+1$, etc., assuming for the sake of simplicity that there is only one instruction per address):

k	*LDS*	n,
$k+1$	*MPY*	$n+10$,
$k+2$	*TOA*	m *),
$k+3$	*SAP*	m.

*) The product now contains twice as many figures, but the part in S can be neglected.

Next the same cycle has to be carried out with the other components of the vector. This can of course be done by repeating these four instructions a further nine times with other values of n. Forty instructions will then have to be stored in the memory and carried out.

We could alternatively increase by one the addresses n and $n+10$ of the instructions in k and $k+1$ and then begin again at k by means of the following seven instructions:

$k+4$	*LDA*	k,
$k+5$	*TOA*	"1" *),
$k+6$	*SAP*	k,
$k+7$	*LDA*	$k+1$,
$k+8$	*TOA*	"1",
$k+9$	*SAP*	$k+1$,
$k+10$	*JUN*	k.

*) Here the number 1 is placed in the instruction itself: the address-interpretation bit is thus 1.

This time 11 instead of 40 instructions must be stored in the memory, but 110 instructions have to be carried out, so that the whole process takes much longer. (Counting is furthermore required to determine when the cycle has been carried out ten times.)

The second series of instructions will, however, become unnecessary if the instructions at addresses k and $k+1$ are modified "odd" by means of the number 1. Before they are carried out, the address part of these instructions is then increased by 1 and in this form the instructions are replaced in the memory. (The first time the addresses must in this case be $n-1$ and $n+9$, as modification also takes place when the instructions are carried out for the first time.) The programme is then reduced to the original four instructions plus a jump instruction, and these have to be carried out 10 times (the requisite counting will again be left out of account). Therefore not more than 5 instructions have to be stored in the memory, and 50 instructions have to be carried out. Instructions with modification each require only $1\frac{1}{2}$ µsec more than the non-modified ones. Compared to the first method there is therefore only a small loss of time, accompanied by great saving of space in the memory. Compared to the second method there is a gain in both respects.

The control of the PASCAL

Let us now consider the control of the PASCAL in greater detail with reference to the block diagram of *fig. 13*. This shows the arithmetical unit *Cal*, the control unit *Con* and the memory *Mem* with their registers. The diagram also shows the paths that can be followed by numbers and instructions (full lines) and by selection signals (broken lines).

We shall follow the working of the machine during the fetching and execution of an instruction. Suppose that it is the turn of the instruction pair at address 51. The number 51 will then be found in the T register, which performs the selection of the address in the memory. Let us further consider the simplest possible situation, viz. that the result of the previous operation is still left in the A register. The selected word with the two instructions I_1 and I_2 comes from the memory and first enters the

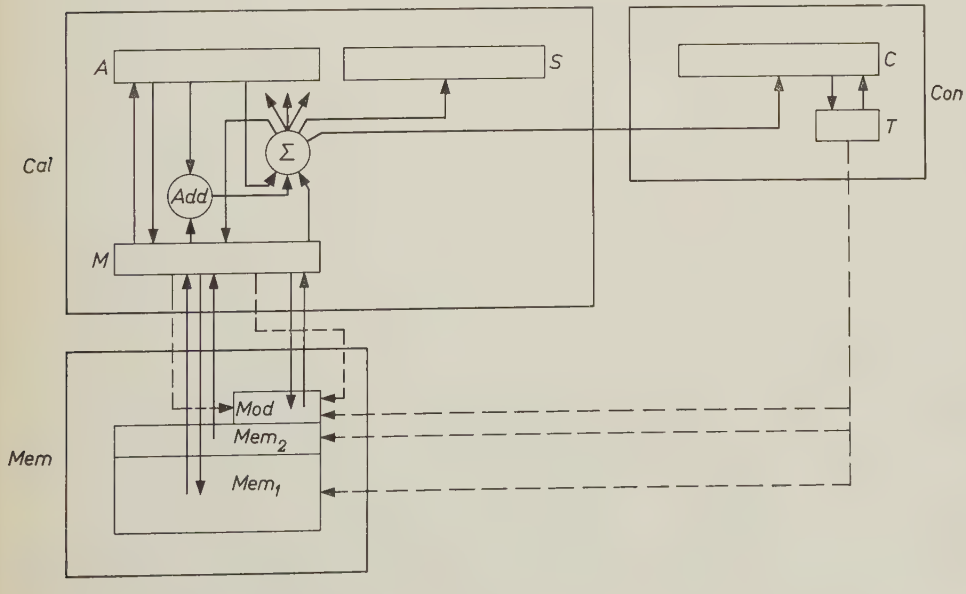

Fig. 13. Block diagram of the PASCAL with the arithmetical unit *Cal*, the control unit *Con* and the memories *Mem*. In the arithmetical unit the registers A, M and S and the adder *Add* are shown. Furthermore the arithmetical unit contains the six-way switch Σ, which at the command of the control unit can make the requisite connection between the various registers and the adder. The transport of numbers and instructions necessary for carrying out the processes is shown by full lines. The broken lines indicate the path of selection signals from the T register to the memory for the fetching of instructions and numbers (Mem_1 is the magnetic-core memory, Mem_2 is the plug-board memory) and from the M register to the modification register *Mod* for fetching the modifications of an instruction.

M register. If the instructions have to be modified, the correct registers must be selected from the 8 modification registers, using the selection circuits connected to the part of the *M* register where the three modification selection bits are to be found. The two modifications (one for each instruction) must now be added to the instructions. For this the *A* register is required, so it must first be cleared. Its contents must however be preserved. These can for the time being be placed in the control register *C*, for the contents of this (the old pair of instructions) may be destroyed. The instruction pair is itself brought from *M* to *A*, while the selected modifications, different for each half-word, go to *M*.

The adder now supplies at its output the instructions in modified form, while in *A* at this instant the instructions are still present in their unmodified form. Depending on the kind of modification (even or odd) one of these two forms is replaced in the memory via *M*. The modified instruction pair is brought to *C* and the original contents of *A* are simultaneously replaced in *A*.

Next the first instruction (I_1) must be performed. Its address part is transferred from *C* to *T* in order to select from the memory the number with which the calculation is to be carried out. The number 51 that stood in *T* must not be lost and is therefore stored for the time being in the corresponding part of *C*. (This exchange is necessary as only *T* can select a word from the memory.) When the desired number has arrived from the memory in *M*, the operation to be performed can start. If this is an addition, it is only necessary for the sum formed in *Add* to be transferred to *A*. This has already been explained above, as has the procedure for other operations.

Once the operation has been completed, a "ready" signal indicates that I_1 and I_2 in the *C* register must be changed, after which the second instruction is carried out. When the "ready" signal of the second instruction is also given, the next instruction pair must be selected from the memory. The address of the old instruction pair, increased by one, is therefore placed in *T* and the whole cycle is repeated.

The PASCAL's special instructions

The designer of computers is still given a chance to show his inventiveness in providing facilities for special instructions, and this is the main reason why the many machines built at the present time get an individual character. In the present section we shall review some of the special instructions that can be handled by the PASCAL. We have already mentioned the *conditional jump* instructions. A special form of these is the jump instruction that depends on the result of a previous *comparison* instruction. By means of a comparison instruction, *COM n*, the number at address *n* is compared with the number in *A*. The three possibilities of "bigger" "equal" and "smaller" determine the positions of two flip-flops. The particular jump instruction might now be, for example: Jump to address *m* if the result of the last comparison was "bigger". The control examines the contents of the two comparison flip-flops and determines whether or not the jump must be carried out. Three jumps of this kind are thus possible.

In view of the fact that the PASCAL contains two instructions per word and that it is necessary to be able to jump both to the I_1 half and to the I_2 half, all the various jumps occur in duplicate; jumps to I_1 have an even instruction number, while those to I_2 have an odd number.

For the *transport* of data from the drum memory to the magnetic-core memory and vice versa the *transport* instructions *DTC* (drum to core) and *CTD* (core to drum) are used. It has already been mentioned in the discussion of the memories that a great saving of time is obtained with the PASCAL because 1) transport may take place in both directions simultaneously, 2) transport may commence at any instant and 3) the machine can in the meanwhile continue computing.

In the PASCAL there is also a *count* and a *repeat* instruction. Both these instructions may only occur in the I_2 half of a word. In the *count* instruction a count is maintained in the address part of the instruction of how many times this instruction has been carried out in the programme; after a number of times that can be set in advance the next instruction is skipped. This is a means of getting out of a cycle. One might imagine, for example, that the count instruction is followed by an instruction: "jump back to the beginning of the cycle"; then this jump backwards will initially be carried out, until after a preset number of times it is omitted.

In the *repeat* instruction the I_1 half of the instruction pair is carried out a preset number of times before the programme continues. In this way one can, for example, carry out a multiplication by 3 by combining a repeat instruction, set to 3 times, with an add instruction in the same instruction-pair. It costs half a word in the memory space, but in fixed-point notation it produces a gain in speed, in view of the fact that three such additions take less time than one multiplication.

Finally let us here discuss the special instructions *link-I* and *link-II* that serve for introducing a subroutine.

A subroutine is a programme that on its own forms a more or less complete entity and that because of its utility in many calculations is cast in a standard form. Such programmes are generally used for the calculation of, for example, sin x, $\sqrt{x}$, log x, and e^x. Usually the subroutines are in stock on a magnetic tape or a punched tape, and it must be possible to insert them into a programme at the place where they are needed. There are, however, advantages in placing a subroutine in an arbitrary row of addresses in the memory, and to include in the (main) programme at whatever position is necessary a jump instruction for jumping to the initial address of the row. After the subroutine has been carried out the machine must then jump back to the place where the main programme was interrupted. It must be possible to use the subroutine in different places of the same main programme, and the instruction which controls the jump back to the main programme must take this into account. Now this is automatically ensured by the link-I instruction. The address part of this instruction contains the address k, say. The subroutine proper begins at $k+1$; the link instruction now puts the subroutine into operation by jumping to $k+1$ and simultaneously places a jump instruction at k, indicating the return jump to the correct part of the main programme. It is then only necessary to make sure that each subroutine will finally jump back to its first address (k); there the machine finds the jump instruction bringing it back to the correct part of the main programme.

Even more flexible in use is the *link-II* instruction. This instruction refers to a subroutine via an "address book". At a fixed position in the memory a small list is made of places where subroutines are stored. This is done in the form of jump instructions referring to their respective initial addresses. In all, 30 subroutines may occur. The link-II instruction now puts into action a subroutine by directing the machine to the relevant number in the small list, after which the transition to the subroutine and the return to the main programme occur completely automatically.

In order to illustrate how a link-II works, we may mention that among the 64 possible instructions, with the operation numbers 0 to 63 given by 6 bits, there are 32 that do not use their 11 address bits in their proper meaning of "position of a number to be fetched or stored". These are instructions in which no number is processed, e.g. the jump instructions, the *DTC* and *CTD* instructions, and the count and repeat instructions. For such instructions an address-interpretation bit equal to 1 would have no sense. If they do however have an address-interpretation bit equal to 1, these instructions all (except the count and repeat instructions) represent link-II instructions in which the operation number indicates directly the number of the subroutine in the list. The advantage of the link-II instructions is that the programmer has at his disposal another 30 operation numbers with which he can indicate computing procedures of his own choice while, just as with normal instructions, he still has room for indicating the number to be processed. Thus one programmer might use these instructions to indicate, for example, an addition, a subtraction, or a multiplication of complex numbers with floating point, while another might perhaps use them for addition, multiplication etc. of matrices.

The parity check

The reader will probably have noticed that in what was mentioned above we have spoken of a word length of 42 bits, but that in Table I mention was made of a total word length of 44 bits. This difference is due to the parity bits. These digits, one per half-word, provide a check on the operation of the machine. They have no significance in either the number or in the instruction, but they ensure that the total number of ones in the relevant half-word is odd.

By means of a special device in the M register the number of ones is investigated and a parity bit (1 or 0) added: each word going from the M register to the memory is thus provided with two appropriate parity bits. If a word from the memory enters the M register, the number of ones is checked again. If this is now found to be even, an error is present and the machine stops. If there are two (or an even number of) errors per half-word, they remain undiscovered; the chance of more than one fault occurring is, however, very small.

Recording on magnetic tape — in which the chance of errors is generally greater — is checked by a number of extra bits in addition to these two parity bits. The 44 bits of a word are recorded in four rows on 14 tracks of the tape. The remaining 12 positions are taken up by check bits.

Input and output facilities in the PASCAL

Punched tape, punched cards, or magnetic tape may be used for the input of the PASCAL. For the output, use can be made of an electric typewriter, a tape punch, a card punch, a line printer and magnetic tape equipment.

The typewriter is much slower than the other output devices. It is therefore used mainly to write out instructions for the operating staff (who need not know what the computing problem was) as indicated by the programme, e.g. to tell them that a new roll of tape must be inserted in one of the magnetic-tape units of the memory.

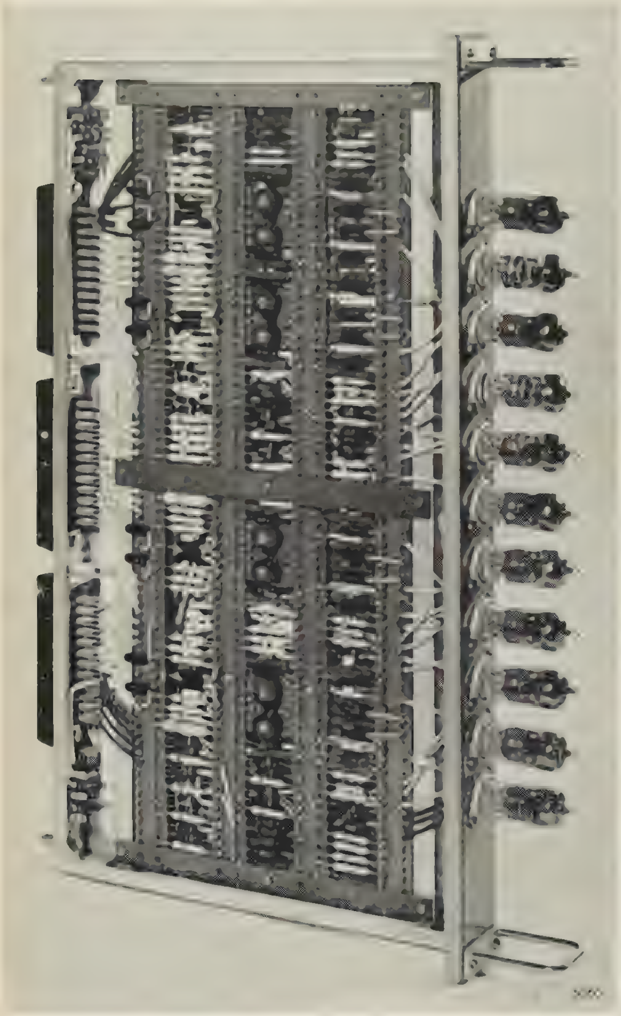

Fig. 14. A circuit panel of the arithmetical unit. This interchangeable element contains all the circuits corresponding to one digit in the arithmetical unit. It embraces the flip-flops of the registers A, M and S, the addition circuit *Add* and the six-way switch Σ. As the numbers to be used have 42 binary digits, the whole arithmetical unit contains 42 of these circuit panels.

The tape punch, the card punch and the magnetic tape are used if the results of computation have to be processed again later on by the machine. If the results must be made available in readable form, use is made of a line printer, which prints a whole line of 90 characters simultaneously at a rate of $2\frac{1}{2}$ lines per second. This speed is frequently still too low for printing the results during computation. It that case a magnetic-tape unit can be used for recording the information very quickly. A separate apparatus can then read these data in groups from the tape and supply them to a fast line printer that prints 10 lines of 120 symbols per second.

Special constructional features of the PASCAL

The PASCAL is built up of interchangeable circuit panels. The size of these elements is determined by the arithmetical unit, since the components of the registers A, M and S, the adder and the six-way switch Σ referring to a single digit are assembled together (*fig. 14*). The arithmetical unit thus has 42 identical elements. An advantage of this system is that not many connections are required among the various circuit panels, so that the wiring of the machine can remain fairly simple for such a complicated apparatus. The size of the circuit panels was also found to suit the rest of the machine extremely well, so that the PASCAL has in all 125 elements, all of the same dimensions and all accommodated in a cabinet 50 × 190 × 270 cm. This cabinet also houses the stabilized voltage-supply unit, the

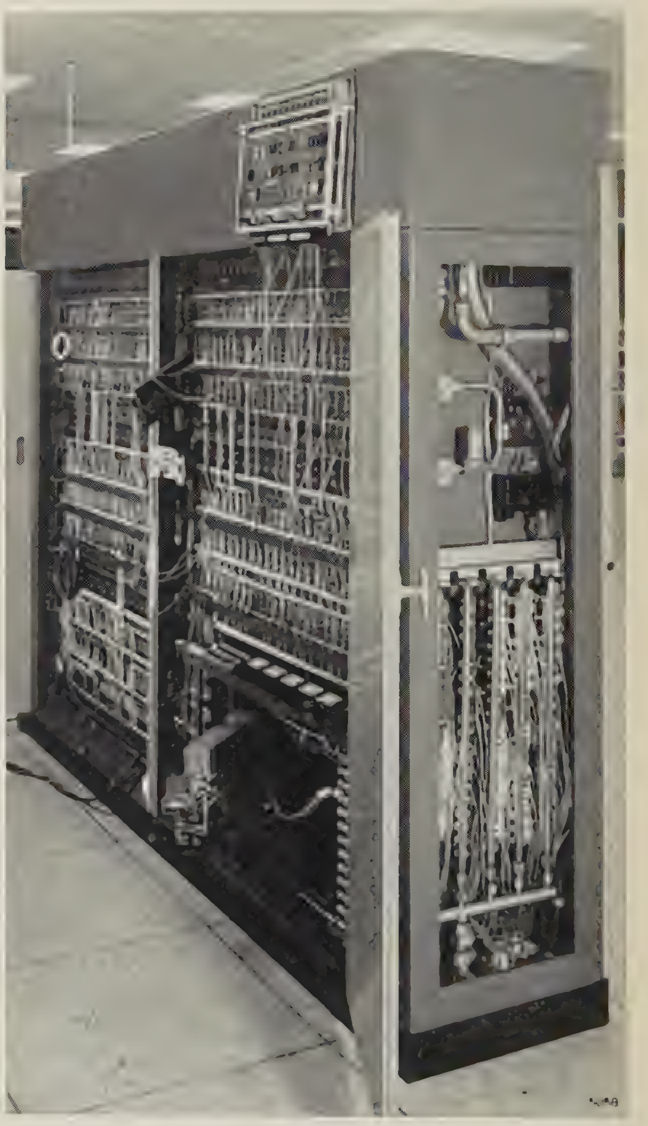

Fig. 15. Rear view of the cabinet in which the principal components of the PASCAL are housed (see fig. 2), during testing of the machine. The doors are open, so that the wiring can be seen. A number of power transistors are visible at the side of the cabinet; these serve for the stabilization of the supply voltages. For reasons of cooling they are mounted on metal strips fixed to tubes in which water flows. The pilot lights at the end of the cabinet are each in series with a transistor and assure an equal distribution of the current over the transistors. They also serve as fuses.

magnetic-core memory and the modification memory. *Fig. 15* shows the cabinet from the rear with the doors opened, so that the wiring can be seen; *fig. 16* shows the front of the cabinet, likewise with the doors opened. In view of the fact that, when the machine was designed, suitably fast transistors were not yet available for a number of functions, the PASCAL contains some 1200 valves. The number of transistors amounts to about 10 000, and the number of germanium diodes to about 15 000.

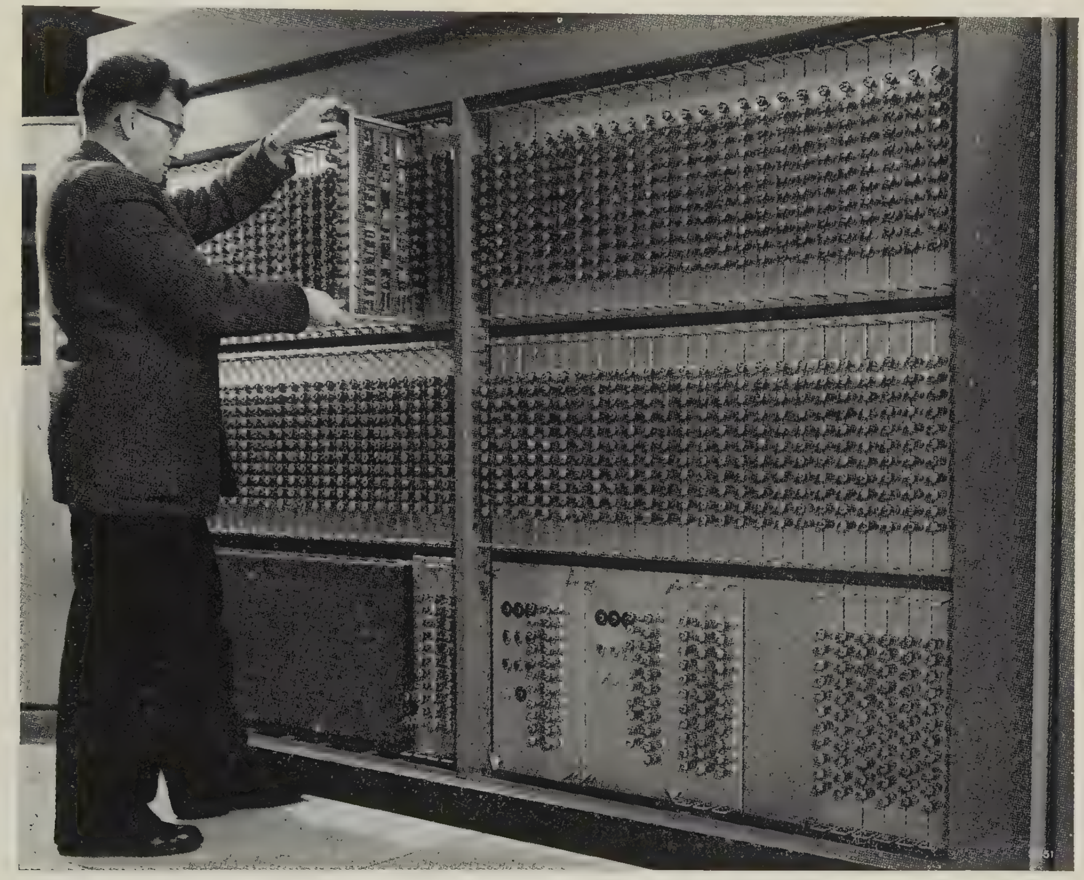

Fig. 16. Front of the cabinet in which the principal components of the PASCAL are housed (cf. fig. 2), with the doors opened. The uppermost row of circuit panels (cf. fig. 14) forms the arithmetical unit. The centre row forms the control unit. Below, from left to right: the power supply unit, the magnetic-core memory and the modification memory. When the cabinet is closed, the heat developed therein is removed by circulating air which is cooled by tap water.

The heat developed in the cabinet amounts to some 10 kW. When the front doors are closed, the cabinet forms a sealed unit. Air circulating inside takes up the heat and is cooled by tap water in a heat exchanger. The opening of the doors at the back does not interfere with the air circulation, so that the wiring and all points that are important for maintenance remain accessible while the machine is working. In fig. 15 can be seen how the power transistors for the stabilization of the supply voltages (at the side of the cabinet) are cooled. They are mounted on metal strips that form a unit with the tubes through which the tap water flows.

The operation of the PASCAL is controlled entirely from the control desk (see figs. 2 and 11). An upright panel contains the switches for starting and stopping the machine as well as the switches for slow operation, sometimes required when it is necessary to follow the various operations visually during maintenance. Pilot lights on the left-hand half of the panel indicate the contents of the *S*, *A* and *M* registers, and ones on the right-hand half indicate the contents of the control register *C* and of *T*. The lowest row of pilot lights on the left shows continuously the contents of an arbitrary memory address that can be selected by means of switches on the right of the panel. Further pilot lights show the state of the two flip-flops for the comparison instruction (see page 14), the state of affairs of transports in the course of being carried out, and the occurrence of any parity errors. A meter in the centre of the panel indicates during what percentage of the time the machine is actually "computing"; the remaining time is used in waiting for transport or for input and output. The plugboard memory is situated in a recess sunk into the top of the control desk proper, while the push-buttons for the address 0 are at the bottom right-hand side of the control panel.

On the far right of the desk there is the punched-tape reader for the input of programmes, and on the left there is the electric typewriter. The tape punch is accommodated in a drawer of the desk.

As already mentioned, the PASCAL and the STEVIN with their addition time of 10 μsec belong to the class of "fast" machines; in various parts of the world there are however already designs ready for machines with a computing speed ten times as great [4]). On the other hand, most machines now in general use have a computing speed about ten times smaller and also a smaller memory.

Modern commercial computers that are comparable with the PASCAL as regards computing speed generally have a more extensive magnetic-core memory. The disadvantage of the PASCAL in this respect is however more or less counterbalanced by the rapid transport between the drum memory and the magnetic core memory. Only when there are less than 8 short operations (such as additions) per word transported will such transport produce a serious lowering of the computing speed.

The STEVIN — identical with the PASCAL — works more rapidly than is required for the solution of most administrative problems. The high speed compensates for the lack of a few features that are usually found in machines designed specifically for administrative work.

Summary. The digital electronic computer PASCAL developed in the Philips laboratories in Eindhoven is a binary machine of the single-address type with a word length of 42 bits (either a number or two instructions are given per word). The machine has a magnetic-core memory as a fast working memory, containing 2016 words, and a drum memory as a slow memory with 16 384 words, as well as several magnetic-tape units on which 10^6 words can be stored per tape. In addition there is a small memory, in which 15 words can be inserted manually by plugs and one word by push-buttons, and a modification memory of 8 half-words.

Computation can be performed in either the fixed-point or the floating-point notation; in the latter the fractional part has a length of 33 bits plus a sign bit, and the exponent has a length of 7 bits plus a sign bit (accuracy of 10 decimal places). In fixed-point notation (accuracy 12 decimal places) an addition requires about 10 μsec and a multiplication about 71 μsec. This great speed is attained by means of circuits which determine the carries in the adder very rapidly and by a very efficient organization of the traffic in the arithmetical unit with the help of a special circuit (the 6-way Σ switch). On the average 60 000 instructions are processed per second.

The input of the programmes and the output of the results can take place by means of punched tape, punched cards or magnetic tape. A line printer can also be used for the output.

Before an instruction, coded in the form of a number, is carried out, it can be modified by the addition of a word from one of eight modification registers. Thereafter the instruction may be replaced in the memory either in its original or its modified form. The PASCAL has several special instructions, e.g. the count and repeat instructions, and the link instructions, which assist in the transition to subroutines stored at arbitrary sites in the memory. There are also special instructions for the transport of data from the drum memory to the magnetic-core memory and vice versa. Such transport can take place simultaneously in both directions while the machine continues computing, albeit with a slightly reduced speed (this reduction amounts at the most to 15%).

After a short discussion of calculations with the binary system, this article gives a survey of the principal components contained in all digital electronic computers, leading on to a general survey of the working of such computers. The above-mentioned special features of the PASCAL are discussed in the second part of the article. After a description of certain constructional details of the PASCAL, such as the cooling (it contains 1200 valves, 10 000 transistors and 15 000 diodes), some concluding remarks are made about the PASCAL in comparison with other machines.

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[4]) A summary of digital electronic computers that are at present available commercially or in a state of development will be found, for example, in: Martin H. Weik, A survey of domestic electronic digital computing systems, United States Department of Commerce, Office of Technical Services, 1955; Isaac L. Auerbach, European electronic data processing — A report on the industry and the state-of-the-art, Proc. Inst. Radio Engrs. **49**, 330-348, 1961 (No. 1).

NEW DEVELOPMENTS IN OXIDE-COATED CATHODES

I. OXIDE-COATED CATHODES FOR LOADS OF 1 TO 2 A/cm^2

II. AN OXIDE-COATED CATHODE WITH A HALF-WATT HEATER FOR CATHODE-RAY TUBES

The first of these articles deals with oxide-coated cathodes designed to be loaded with current densities several times higher than ordinary oxide-coated cathodes can withstand, and which yet have a life of a few thousand hours. Although these new cathodes cannot rival the L type of dispenser cathode as regards their permissible current density, they are cheaper and have a lower operating temperature, which removes the problem of insulation between heater and cathode.

Where cathode-ray tubes are used in fully transistorized, battery-fed equipment, such as television receivers, television cameras, oscilloscopes, etc., low power consumption by the heater is an important consideration. The second article concerns an oxide-coated cathode developed for applications of this kind, whose heater consumes only 0.5 W.

I. OXIDE-COATED CATHODES FOR LOADS OF 1 TO 2 A/cm^2

by H. J. LEMMENS *) and P. ZALM *).

621.3.032.213.23:621.3.032.213.63/.64

In specifications of the maximum permissible loading of oxide-coated cathodes in vacuum tubes it is normally stated that the average current density at the cathode surface should not exceed 0.5 to 1 A/cm^2 [1]). This limitation is due to the resistance of the oxide coating and in some cases also to the interface resistance in the cathode. With increasing load the dissipation I^2R in the oxide coating rises in proportion to the square of the thermionic current I, whereas the power which the emitted electrons drain from the cathode rises only in direct proportion to I, being equal to

$$I\left(\varphi + V_{\mathrm{m}} + \frac{2kT}{e}\right),$$

where φ is the work function, V_{m} the potential barrier (a few tenths of a volt) due to the space charge, k is Boltzmann's constant, T the absolute temperature of the cathode, and e the charge of the electron. Above a certain current I, therefore, I^2R is greater than the power drained off by the electrons. The emissive layer can become overheated under these conditions; the thermionic current will then no longer be constant and the oxide coating will be damaged [2]).

For loads greater than 1 A/cm^2, dispenser cathodes [3]) are generally preferred; the emissive surface of these cathodes consists of porous tungsten, activated by adsorption of Ba and BaO. The latter are either supplied from a chamber behind the porous tungsten body (L cathode [4])) or are incorporated in the body itself (impregnated cathode [5])). In these dispenser cathodes the *metallic* character of the emitter predominates. The emissive layer is less than 1 μ thick, and consequently has a very low resistance R. Dispenser cathodes have two drawbacks, however. The first is their relatively high price (due to their rather complicated construction), which limits their use to special tubes. The second is that they have to operate at higher temperatures than oxide cathodes (at 1050-1100 °C as against 740-830 °C), which is a point of importance where low heater consumption is required. Moreover, the higher temperature causes difficulties with the insulation between heater and cathode.

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*) Research Laboratories, Eindhoven.

[1]) D. A. Wright, A survey of present knowledge of thermionic emitters, Proc. Instn. Electr. Engrs., Part III, **100**, 125-142, 1953.
A. H. W. Beck, High-current-density thermionic emitters: a survey, Proc. Instn. Electr. Engrs., Part B, **106**, 372-390, 1959.

[2]) In considering the maximum permissible load we are concerned only with its influence on the emission of the cathode, and not with the limits set to this load by the effect which the resistance of the cathode has on the electron-tube characteristic.

[3]) A. Venema, Dispenser cathodes, I. Introduction, Philips tech. Rev. **19**, 177-179, 1957/58.

[4]) H. J. Lemmens, M. J. Jansen and R. Loosjes, A new thermionic cathode for heavy loads, Philips tech. Rev. **11**, 341-350, 1949/50.

[5]) R. Levi, Dispenser cathodes, III. The impregnated cathode, Philips tech. Rev. **19**, 186-190, 1957/58.

Functions of the oxide coating

On the face of it, the obvious way of solving the resistance problem of oxide-coated cathodes would be to make their emissive layer very thin too (e.g. between 5 and 20 μ), particularly since it is known that the work function of cathodes with such a thin oxide coating is the same as that of cathodes with the usual layer thickness of about 80 μ. The solution fails, however, if a reasonably long life is required of the cathode. An examination of the functions of the oxide coating will make this immediately evident. Its primary function, of course, is to emit electrons. Scarcely less important, however, is its function as the "storehouse" for replenishing the emissive surface [6]). As various investigations have shown [7]), in conventional cathodes coated with barium-strontium oxide the emissive layer, formed by minute crystals of (Ba,Sr)O, consists of virtually pure SrO at the boundary between oxide and vacuum. At the surface — and perhaps inside the crystals too — this SrO layer is activated by Ba and governs the work function of the cathode. As we shall presently see, Ba is used up during emission (some reacting to give the silicate and some being released as metal and evaporating); continuous replenishment of Ba is therefore necessary, and this is ensured by the reaction of BaO with the activators in the nickel of the cathode (Al, Mg, Si, etc.) [8]), and probably also by electrolysis of the oxide coating [6]).

The separation of these two functions — thermionic emission and barium replenishment — has led to the development of two types of oxide-coated cathode for heavy loads:

a) a "storage" cathode, for current densities from 1.5 to 2 A/cm², and

b) a double-coated cathode, for current densities from 1 to 1.5 A/cm².

The storage oxide cathode

One possible construction of a storage type of oxide-coated cathode is shown in *fig. 1*. A nickel cylinder *1* is pressed in at the top so as to form a chamber *2*, which is filled with a reserve supply of, say, (Ba,Sr)O. The chamber is capped by a piece of nickel gauze *3*, to which the emissive oxide coating *4* is applied.

The object of this design is to eliminate the above-mentioned drawbacks of normal oxide-coated cathodes: the formation of an interface resistance, the accompanying change in the composition of the emissive layer during operation, and excessive resistance in the oxide coating.

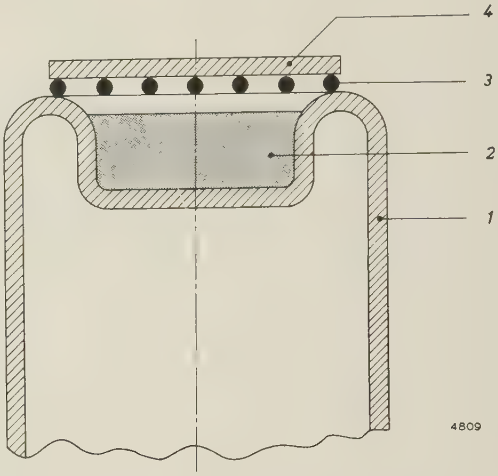

Fig. 1. Cross-section of a storage oxide cathode. *1* nickel cylinder. *2* storage chamber, filled with e.g. (Ba,Sr)O. *3* nickel gauze (exaggerated for clarity). *4* emissive oxide coating.

Avoidance of interface resistance

In normal oxide-coated cathodes the nickel serves a dual purpose: it is the base for the emissive layer and the source of the activating elements, Al, Mg, Si, etc. A consideration affecting the choice of the composition of the cathode nickel is that the products of the reaction between the activators and Ba should not give rise to excessive resistance between the nickel and the oxide. On the other hand, sufficient Ba must be produced for the emissive layer. With the design illustrated in fig. 1, interface resistance between gauze and oxide can be avoided if the composition of the nickel used for the gauze is suitably chosen, the barium for activating the emissive layer being drawn from the chamber through the reaction of its contents with activators in the nickel cylinder and with any metallic powders that may have been added. If the nickel contains Si as activator, the fillings found suitable are:

(Ba,Sr)O, possibly mixed with 3% by weight of Ti (added as titanium hydride), and

$BaAl_2O_4$ with 25% by weight of Ti.

The reaction between BaO and Ti is

$$BaO + \tfrac{1}{2}Ti \rightleftarrows Ba\,(g) + \tfrac{1}{2}TiO_2\,, \quad . \quad . \quad (1)$$

where (g) indicates that the barium is produced in gaseous form. The equilibrium vapour pressure p_{Ba} of the barium (in mm Hg) is given for this reaction by

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[6]) L. S. Nergaard, The physics of the cathode, R.C.A. Rev. **18**, 486-511, 1957.

[7]) H. Gaertner, Electron diffraction on oxide-coated filaments, Phil. Mag. **19**, 82-103, 1935.
J. A. Darbyshire, Diffraction of electrons by oxide-coated cathodes, Proc. Phys. Soc. London **50**, 635-641, 1948.
H. Huber and S. Wagener, Die kristallographische Struktur von Erdalkaligemischen. Untersuchungen mit Hilfe von Röntgen- und Elektronenstrahlen an Oxydkathoden, Z. techn. Phys. **23**, 1-12, 1942.

[8]) E. S. Rittner, A theoretical study of the chemistry of the oxide cathode, Philips Res. Repts **8**, 184-238, 1953.

$$\log p_{\mathrm{Ba}} = -\frac{14\,000}{T} + 8.72$$

(with T in °K), and for the reaction

$$\mathrm{BaAl_2O_4} + \tfrac{1}{2}\mathrm{Ti} \rightleftarrows \mathrm{Ba\,(g)} + \mathrm{Al_2O_3} + \tfrac{1}{2}\mathrm{TiO_2} \quad (2)$$

it is given by

$$\log p_{\mathrm{Ba}} = -\frac{19\,400}{T} + 7.6.$$

This means that, at an operating temperature of $T = 1050$ °K, the maximum Ba vapour pressure in reaction (1) is 2.5×10^{-5} mm Hg, and in reaction (2) only 1.6×10^{-11} mm Hg. These are important data for the application of storage cathodes. Where electron tubes are concerned whose vacuum conditions are not all too good, e.g. because thorough degassing of the metal parts is not readily possible, some generation of barium vapour is an advantage, in that the vapour counteracts poisoning of the cathode by the residual gases. In high-vacuum tubes, on the other hand, the lowest possible Ba vapour pressure may be desirable to avoid grid emission caused by barium deposits on the grid.

The formation of interface resistance is not the only adverse consequence of the reaction of the activator in the cathode nickel with the BaO; another is a change in the composition of the oxide coating. If the cathode nickel contains, for example, 0.1% by weight of Si as activator, more than 10% of the BaO present may react with the Si to form $\mathrm{Ba_2SiO_4}$ [9]) at the interface of the nickel and the oxide coating. (This estimate relates to a coating of 10 mg of (Ba,Sr)O per cm^2 on nickel 100 μ thick.) Moreover, in this case just as much Ba will evaporate as will form silicate by the reaction:

$$4\,\mathrm{BaO} + \mathrm{Si} \rightleftarrows \mathrm{Ba_2SiO_4} + 2\,\mathrm{Ba\,(g)}\,.$$

Minimizing the resistance of the oxide coating

The resistance of the oxide layer has already been mentioned as one of the drawbacks of normal oxide-coated cathodes. The emissive coating of a storage cathode, however, can be relatively thin, and thus its resistance low. Higher permissible loading makes it possible to operate this cathode at a lower temperature than ordinary (Ba,Sr)O-coated types. This reduces the tendency of the oxide coating to lose its porosity through sintering. Since the conduction of the emissive layer is largely governed by electron transport through the pores between the crystals [10]), this again has the effect of keeping down the resistance of the coating. In addition, a more open structure will ensure better dispensation of Ba to the boundary face between oxide and vacuum.

A further way of minimizing the sintering process is to use another oxide instead of (Ba,Sr)O. Substances which have proved suitable are SrO, (Ca,Sr)O and CaO. During operation, coatings of these substances do not lose their porosity to the same extent as (Ba,Sr)O, and consequently the increase in their resistance is less marked.

Results with storage oxide cathodes

It will be clear from the foregoing that there is no essential difference between conventional oxide-coated cathodes and the storage types described. The latter, however, have more favourable characteristics. Before demonstrating these, we shall recall a dictum of Nergaard: "Every cathode is in equilibrium with its environment" [6]). It is possible, for example, to subject a normal (Ba,Sr)O cathode for a long period of time to a continuous load of 1 A/cm^2, provided the residual gases have been sufficiently removed by careful degassing. The nickel used for such a cathode cylinder can be given a low activator content, as a result of which the composition of the oxide coating remains fairly constant during the life of the cathode and no appreciable interface resistance is found. A storage cathode, however, where the cylinder consists of Si-activated nickel, the filling of (Ba,Sr)O, and the emissive coating on the gauze is also (Ba,Sr)O, can have a life of more than 5000 hours under a constant load of 1.5 A/cm^2 (curves *a* and *b* in *fig. 2*), in conditions which a normal oxide-coated cathode is unable to withstand for as much as 200 hours (curve *c* in fig. 2).

Cathodes whose emissive layer consists of SrO, CaO or mixed crystals of (Ca,Sr)O differ little in their characteristics from types coated with (Ba,Sr)O; the work function of cathodes coated with SrO is almost the same, with CaO slightly higher and with (Ca,Sr)O perhaps somewhat lower. The characteristics of the latter type are optimum when the mole fraction of CaO is 60%.

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[9]) X-ray and chemical analyses have shown the composition of the interface to be $\mathrm{(Ba_{0.8},Sr_{0.2})_2SiO_4}$.

[10]) R. Loosjes and H. J. Vink, The conduction mechanism in oxide-coated cathodes, Philips Res. Repts 4, 449-475, 1949.
R. Loosjes and H. J. Vink, Conduction processes in the oxide-coated cathode, Philips tech. Rev. **11**, 271-278, 1949/50.

The work function of cathodes can in principle be found from Richardson's equation:

$$J_s = AT^2 \exp\left(-\frac{e\varphi}{kT}\right),$$

where J_s is the saturation current density. The emissive surface of an oxide-coated cathode, however, is not homogeneous. The work function, therefore, is not everywhere identical and in practice is expressed by a suitably weighted mean. The values given below were found either from the slope of the line giving $\ln J_s/T^2$ as a function of $1/T$, or by inserting the value 120 A/cm^2(°K)^2 for A. By the first method the work function of cathodes coated with (Ca,Sr)O is found to be 1 eV; the second method gives 1.37 eV at 900 °K and 1.42 eV at 1020 °K.

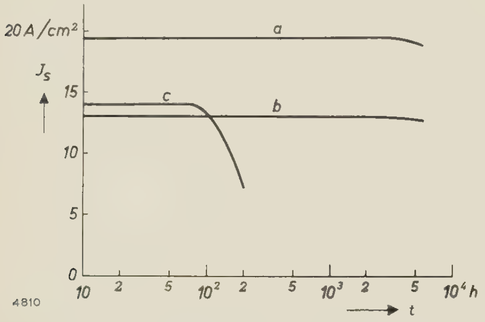

Fig. 2. Saturation current density J_s of various oxide-coated cathodes, as a function of the time t during which they were continuously loaded at 1.5 A/cm^2. Curves a and b relate to storage cathodes, as illustrated in fig. 1, operated at 780 °C and 730 °C, respectively. Diameter of emitting surface 1.5 mm, chamber contains (Ba,Sr)O mixed with 3% by weight of Ti, coating is pure (Ba,Sr)O. Curve c relates to a normal oxide-coated cathode, operated at 820 °C.

The double-coated cathode

After what has been said about the storage type of oxide-coated cathode, the principle of the double-coated type can be stated quite simply. It differs from the conventional type in only one respect. Ordinarily the Ba activation is due to the BaO reacting with an activator originating from the cathode nickel; in the double-coated type the activator is entirely or partly incorporated in the oxide layer, Ti or Zr being added as hydrides to the (Ba,Sr)CO$_3$ sprayed on to the nickel base. Since the presence of the activator in the entire emissive layer proves to have an adverse effect on the emission characteristics, a second coating containing no activator is sprayed on to the first. This second coating may consist of (Ba,Sr)CO$_3$, (Ca,Sr)CO$_3$, (Ba,Ca,Sr)CO$_3$, etc. After decomposition of the carbonates and activation, the cathode obtained is again essentially a storage type, but in this case the barium-producing layer and the emissive layer are in direct contact with one another.

The characteristics of the double-coated cathode lie between those of the ordinary oxide-coated type and those of the storage type. At a current density of 1.5 A/cm^2 it has a life of between about 1200 and 1500 hours, and at 1 A/cm^2 between about 2000 and 2500 hours. Its performance is thus inferior to that of the storage cathode, but it has the compensatory advantages of simpler construction and a lower price.

II. AN OXIDE-COATED CATHODE WITH A HALF-WATT HEATER FOR CATHODE-RAY TUBES

by F. H. R. ALMER *) and A. KUIPER *).

621.3.032.213.6

The advent of the transistor and the crystal diode has led, or is leading, to the development of portable battery-fed electronic equipment containing cathode-ray tubes, such as television receivers, television cameras and oscilloscopes. The power consumed by the C.R.T. heater in such equipment constitutes a heavy load on the battery. The cathodes in standard, mains-operated picture tubes in America, for example, use a 4-W heater. Philips C.R.T. cathodes consume only about 2 W (6.3 V × 0.3 A), but even that is a severe drain on a battery.

There is thus a need for a cathode for cathode-ray tubes of equivalent performance that will consume considerably less than 2 W. In the following a cathode is discussed for which the heater power is only 0.54 W at a heater voltage of 6.3 V. This cathode is now fitted in oscilloscope tubes (type DH 7-11) and in vidicons (type 55 850). The design described offers prospects of using higher heater voltages, e.g. 12 V, which in many cases is the most favourable supply voltage for transistors.

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*) Electron Tubes Division, Eindhoven.

The power taken up by the heater is dissipated partly by radiation and partly by thermal conduction through the heater terminals and the cathode supports. Both the radiation and the conduction must be reduced to achieve any appreciable reduction in heater power. Which of the two is reduced more than the other is a matter of some importance, as will be shown below.

One of the main points to be observed in the design of a cathode is the possible spread in its working temperature. Below a certain minimum temperature the thermionic emission is too small; above a certain maximum temperature the life of the cathode is shortened and the emissive material will evaporate to such an extent as to endanger the insulation between the electrodes. The cathode temperature may deviate from the desired value for the following reasons:

1) The heater power is incorrect,
    a) because the supply voltage differs from the rated value,
    b) because of unavoidable differences in the heaters themselves.
2) The heat balance of the heater + cathode assemblies shows a statistical spread for a given heater power.

The reason mentioned under 1(*a*) — different supply voltage — applies especially to cathodes fed from batteries, whether accumulators or dry cells, the voltage of which shows relatively much greater variations than most AC mains.

Other requirements to be met by such cathodes are:

1) the ability to withstand shocks and vibrations,
2) good insulation between heater, cathode and Wehnelt cylinder,
3) the ability to heat up quickly, so that the television picture becomes visible very soon after switching on.

These questions are discussed below.

Reasons for spread in cathode temperature

Variations of the heater voltage

The influence of variations in the heater voltage V_f on the temperature T_k of the cathode can be subdivided into

a) the effect of variations in V_f on the power P_f taken up by the heater ¹), and
b) the effect of variations in P_f on the temperature T_k.

If we call the heater current I_f, then $P_f = V_f I_f$, and so

$$\frac{\mathrm{d}P_f}{P_f} = \frac{\mathrm{d}V_f}{V_f} + \frac{\mathrm{d}I_f}{I_f}.$$

Let c be the ratio of the differential resistance $\mathrm{d}V_f/\mathrm{d}I_f$ of the heater to the resistance V_f/I_f, then

$$\frac{\mathrm{d}I_f}{I_f} = \frac{1}{c}\frac{\mathrm{d}V_f}{V_f},$$

and therefore

$$\frac{\mathrm{d}P_f}{P_f} = \left(1 + \frac{1}{c}\right)\frac{\mathrm{d}V_f}{V_f}. \quad \ldots \quad (1)$$

The relative variation of the heater power for a given relative variation of the heater voltage thus decreases as the factor c increases. In well-designed indirectly heated cathodes the value of c is between 1.6 and 2.0, depending on the heater temperature and the construction, and the factor $(1 + c^{-1})$ is therefore between 1.63 and 1.50. Here, then, there is not much chance of improvement.

The effect of variations in P_f on the cathode temperature T_k depends to a great extent on how the power P_f is removed from the cathode. The two processes responsible for its removal are radiation and thermal conduction (via the cathode supports and the pins which make the electrical connections). Let us first consider a cathode whose power is almost entirely dissipated by conduction. As an approximation we may then write:

$$T_k - T_0 \propto P_f,$$

where T_0 is the ambient temperature. Turning to the other extreme, we may write for a cathode which dissipates its heat almost entirely by radiation:

$$P_f = C(T_k)\,(T_k^4 - T_0^4)\,,$$

where C is a factor dependent on the temperature. In an oxide-coated cathode T_k is roughly 1070 °K and T_0 about 350 °K, which means that T_0^4 is barely 1% of T_k^4. In our following considerations we shall therefore disregard T_0^4 in relation to T_k^4. Furthermore, in a limited temperature range around the nominal cathode temperature the factor C can be replaced by a constant factor and the exponent 4 by a larger exponent n; we then have $T_k^n \propto P_f$, so that

$$T_k \propto P_f^{1/n}.$$

Evidently, then, in the case of a cathode which is a pure radiator T_k depends much less on P_f than in the other case, where all heat is dissipated by conduction. We therefore conclude that, in order to

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¹) We consider here only the most unfavourable case where no other heaters or resistors are connected in series with the heater, i.e. where V_f is equal to the supply voltage.

minimize the dependence of T_k on V_f, *the dissipation of the heat by conduction should be limited as much as possible in favour of its removal by radiation.*

Let the power removed from the cathode by radiation be βP_f; that removed by conduction is then $(1-\beta)P_f$. The heat balance can therefore be written:

$$\begin{aligned} P_f &= \beta P_f + (1-\beta)P_f \\ &= k_1 T_k^{\,n} + k_2(T_k - T_0)\,, \end{aligned} \quad . \; . \quad (2)$$

where k_1 and k_2 are proportionality factors.

Again in a limited temperature range (e.g. from 1000 to 1200 °K) we may write:

$$P_f \propto T_k^{\alpha}\,. \quad . \; . \; . \; . \; . \; . \quad (3)$$

The exponent α can be determined by measuring T_k on the cathode as a function of P_f. We can then calculate the magnitude of the fractions β and $1-\beta$ for the cathode in question, i.e. the fractions of P_f that are dissipated by radiation and conduction respectively, using the following relationship between α and β:

$$\beta = \frac{\alpha - \dfrac{T_k}{T_k - T_0}}{n - \dfrac{T_k}{T_k - T_0}}\,. \quad . \; . \; . \; . \; . \quad (4)$$

The exponent n is only slightly temperature-dependent; e.g. for nickel, $n \approx 4.6$ in the entire temperature range from 600 to 1200 °K. Disregarding $\mathrm{d}n/\mathrm{d}T_k$ therefore, we find from (2):

$$\frac{\mathrm{d}P_f}{\mathrm{d}T_k} = n\,k_1\,T_k^{\,n-1} + k_2 = \frac{n}{T_k}\,\beta P_f + \frac{1-\beta}{T_k - T_0}\,P_f\,,$$

or

$$\frac{\mathrm{d}P_f}{P_f} = \left[n\beta + (1-\beta)\frac{T_k}{T_k - T_0}\right]\frac{\mathrm{d}T_k}{T_k}\,. \quad . \; . \; . \quad (5)$$

From (3) we find:

$$\frac{\mathrm{d}P_f}{P_f} = \alpha\,\frac{\mathrm{d}T_k}{T_k}\,. \quad . \; . \; . \; . \; . \; . \; . \; . \quad (6)$$

We then obtain from (5) and (6):

$$\alpha = n\,\beta + (1-\beta)\frac{T_k}{T_k - T_0}\,.$$

Solving this expression for β, we arrive at (4).

Fig. 1 shows a plot of T_k versus P_f for $\alpha = 1$, $\alpha = 3$ and $\alpha = 4$. It can be seen that the dependence of T_k on P_f decreases as α increases, and, as appears from (4), a larger α is associated with a larger β, that is with a greater heat loss by radiation and a smaller loss by conduction. In agreement with our foregoing calculations, then, the effect of reducing the loss by thermal conduction is indeed favourable.

The marked dependence on α shown by the ratio $\beta/(1-\beta)$ between radiation and conduction losses appears from the figures in *Table I*, which refer to two different designs ($T_k = 1080$ °K, $T_0 = 350$ °K, $n = 4.65$, $\alpha = 3.0$ and 3.8).

Table I.

	α=3.0	α=3.8
β	0.48	0.80
$1-\beta$	0.52	0.20

Fig. 2 shows T_k as a function of the heater voltage V_f for $\alpha = 3$ and 4.

Variations of the heat balance of heater + cathode assemblies

Various specimens of the same type of cathode, operated at identical heater power, show differences in temperature owing to the unavoidable statistical spread in the heat balance of heater + cathode assemblies. An extensive investigation has shown that the main cause of this spread is an undefined heat loss at places where there is fairly loose thermal contact between components at different temperatures, e.g. the cathode body and the ceramic or mica disc to which the cathode body is secured. As regards

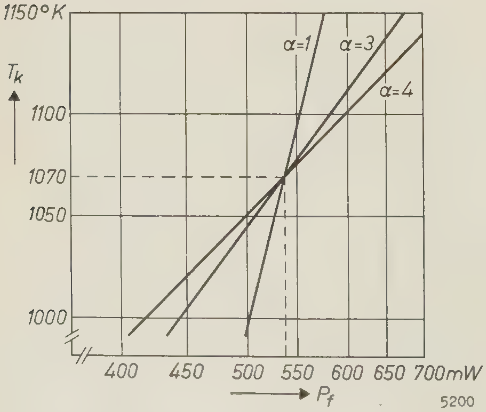

Fig. 1. Temperature T_k of a cathode as a function of heater power P_f, for various values of the exponent α in (3).

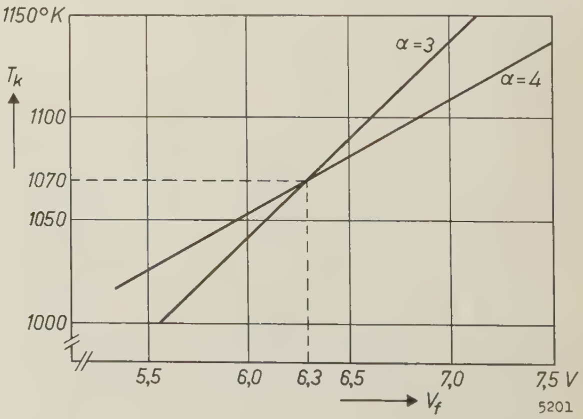

Fig. 2. As fig. 1, but now with the heater voltage V_f as abscissa.

radio tubes of conventional construction and comparable P_f, the standard deviation σ from the nominal cathode temperature is generally 20 °C [2]). Similar and even greater standard deviations are found where the cathodes used in cathode-ray tubes are mounted in ceramic discs, as is the case in America. The standard deviation of the 2-W cathode now fitted in Philips television picture tubes has been reduced to 10 °C by ensuring a defined heat loss through welded metal supports (of poor thermal conductivity). A similar method has been used (see below) to give the half-watt cathode the same low standard deviation of 10 °C.

Design of the new cathode

To draw up the heat balance of the new cathode we must start from various data that are more or less fixed beforehand.

1) Situated opposite the cathode, at a distance of 50 to 150 μ, is the Wehnelt cylinder, which has a bore of 1 mm or less. Since the size of the bore and its positioning in relation to the emissive coating show slight differences for different electron guns, the smallest linear dimension of the emissive surface must not be less than 1.4 mm. The minimum surface area must therefore be 2.0 mm².
2) At an operating temperature of 800 °C the emissive surface of 2.0 mm² radiates 60 mW (or less, depending on the reflexion coefficient of the Wehnelt cylinder).
3) The cathode body must accommodate the heater together with its insulation. Taking the maximum heater voltage of 12 V mentioned in the introduction, and having regard to the minimum diameters in which tungsten wire is readily workable in mass production, we see that the minimum volume of the cathode body must be about 2.5 mm³.
4) For practical reasons the nickel body of the cathode (volume ≈ 2.5 mm³) is made rectangular: length 3.5 mm, cross-section 0.5 × 1.4 mm.

The outside surface area of the cathode body is 14.5 mm², only 2 mm² of which is occupied by the emissive layer. The nickel surface of 12.5 mm² radiates 200 mW at an operating temperature of 800 °C [3]). One end of the body is closed, the other can be partly closed by a lug after insertion of the heater. Some heat is still lost through the opening which is left, however. The heater further loses heat by radiation from the leads outside the cathode and by conduction via the heater terminals. For these three items a total of 180 mW was measured. At a rough estimate, the open end accounts for 100 mW of this total and the heater ends for 80 mW; half of the latter may safely be regarded as radiated. The total radiated power is thus about 60 + 200 + 100 + 40 = 400 mW. It being technically feasible to limit the loss through the cathode supports to 100 mW, the total heat removed by conduction is about 40 + 100 = 140 mW. The heater power P_f is consequently 400 + 140 = 540 mW, a value which is low enough for the applications mentioned at the outset. The radiated fraction β and the conducted fraction $1 - \beta$ of P_f are thus 74% and 26%. This roughly corresponds to $a = 3.8$ in Table I, i.e. the cathode temperature depends relatively little on the heater voltage (fig. 2), just about as little as in the case of the 2-W cathode.

The detailed heat balance is set forth in *Table II*; the figures relating to the present 2-W cathode are given alongside for comparison.

Table II. Detailed heat balance of the present 2-W cathode for cathode-ray tubes and of the new half-watt cathode.

	Present 2-W cathode	New half-watt cathode
Radiation from oxide coating	90 mW	60 mW
Radiation from nickel surface	760 mW	200 mW
Radiation from open end	400 mW	100 mW
Radiation from heater leads	100 mW	40 mW
Conduction via heater leads	100 mW	40 mW
Conduction via cathode supports	440 mW	100 mW
	1890 mW	540 mW
$P_f = V_f I_f$	6.3 V × 300 mA	6.3 V × 86 mA

Construction of the half-watt cathode

Fig. 3 shows a magnified photograph of the new cathode. The details are to be seen more clearly in *fig. 4a* and *b*, where a model 15 times actual size is shown.

The cathode body *1* has the dimensions stated above, so that it radiates about 360 mW. It is supported by two nickel-iron strips *6* of low thermal conductivity. Being long and thin they account for a heat loss by conduction of no more than 100 mW. To make the cathode capable of withstanding the shocks to which portable apparatus are exposed, the strips are fitted with a reinforcement rib 7 and "wings" *8*. These wings rest on the upper of the three

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[2]) The "standard deviation" is a convenient and widely used measure of spread; see for example P. J. McCarthy, Introduction to statistical reasoning, McGraw-Hill, New York 1957, p. 111 et seq.
In a Gaussian distribution of an infinitely large batch, 32% deviates by more than σ from the nominal value, 4.5% by more than 2σ, and 0.3% by more than 3σ.

[3]) This does not contradict the statement under (2) that the emitting surface of 2 mm² radiates 60 mW. The radiation coefficient of the total radiation (of all wavelengths) from nickel is only about half that of the emissive material.

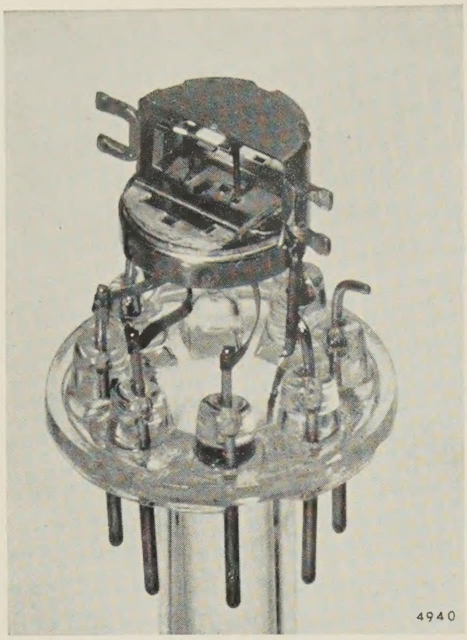

Fig. 3. Half-watt cathode for cathode-ray tubes. $V_f = 6.3$ V, $I_f = 86$ mA.

mica discs (*10*, *11*, *12*) in which the strips are secured, and prevent lateral movement. Shocks and vibrations in the longitudinal direction can do little harm, as the two supports form a parallelogram with the cathode body and the mica discs; any lengthwise displacement of the cathode is therefore accompanied by a much smaller vertical movement towards the neighbouring electrode.

Mounting the cathode supports in mica discs might not seem conducive to a small spread in temperature. The conditions are chosen in such a way, however, that any variable thermal contact that may arise between the supports and the mica will not significantly affect the temperature of the cathode. We can explain how this is done with the aid of *fig. 5*. The thermal resistances are drawn as electrical resistances; k represents the cathode, R_1 and R_2 the thermal resistance of the part of the supports above and below the mica, R_3 the variable contact resistance, and R_4 the thermal resistance of the mica, which is surrounded by the Wehnelt cylinder g_1. The ratio $R_1 : R_2$ and the spacing between cathode and mica are now chosen so that the temperature of the contact point P differs only slightly from the temperature to which the mica is raised, mainly by the heat radiated from the cathode. (T_k is 800 °C, at P the temperature is between 400 and 500 °C, and the mica is at about 300 °C.) The variable contact resistance R_3 thus joins points at only slightly different "potentials", so that the "potential" T_k of the cathode is virtually independent of the magnitude of R_3.

The heater consists of the conventional coiled tungsten wire. To make proper use of the space inside the cathode body, the windings are made oblong on a double mandrel (*fig. 6a*). Tungsten

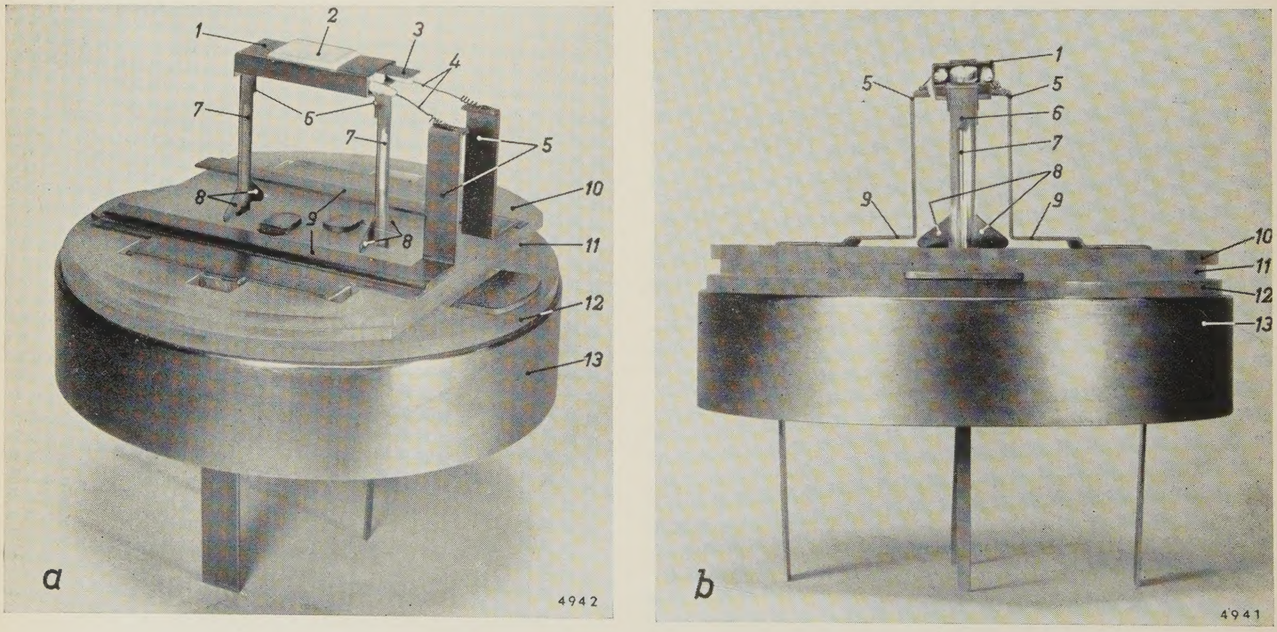

Fig. 4*a* and *b*. Model of the half-watt cathode (linear dimensions 15 times actual size). *1* nickel cathode body, with emissive portion *2*. The lug *3* can be folded to reduce radiation through the open end. *4* straight ends of heater wires. *5* heater terminals. *6* cathode supports of nickel-iron, with reinforcement rib *7* and wings *8*. *9* screen to prevent the formation of metal deposits on mica disc *10*. *11* and *12* mica discs. The diameter of *11* is smaller than that of *10* and *12*, to produce a long creep path (labyrinth) between *5* and *6* on the one part and the metal ring *13* on the other. The Wehnelt cylinder (not shown) is fixed to *13*.

wire of 30 μ diameter can be reproducibly wound in this way with a pitch of 45 μ. The wound mandrel is bent into an M shape and given the usual insulating coating of aluminium oxide (fig. 6*b* and *c*). The wires projecting outside the cathode body are left straight so as to reduce their radiating surface, but the ends are coiled to make them better visible for welding.

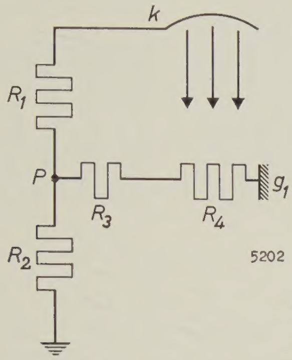

Fig. 5. Thermal resistances are shown here as electrical resistances and temperatures are treated as electrical potentials. *k* cathode, with temperature $T_k = 800$ °C. R_1, R_2 thermal resistance of cathode supports above and below the mica discs. *P* point where the supports touch the mica. R_3 variable contact resistance. R_4 thermal resistance of mica. g_1 Wehnelt cylinder. The ratio $R_1 : R_2$ and the distance between cathode and mica are chosen so that the temperature at *P* (400-500 °C) differs little from the temperature acquired by the mica as a result of cathode radiation (about 300 °C). The magnitude of R_3 therefore has little influence on T_k.

Metal deposits on the mica might cause bad electrical insulation between heater, cathode and Wehnelt cylinder. The heater leads are therefore provided with a screen (*9* in fig. 4*b*) which shields the underlying part of the mica *10*. A further safeguard is the smaller diameter of the mica *11* sandwiched between *10* and *12*, which creates a long creep path (labyrinth) between the Wehnelt cylinder (*13*) on the one part and the cathode and heater on the other (see fig. 4*b*).

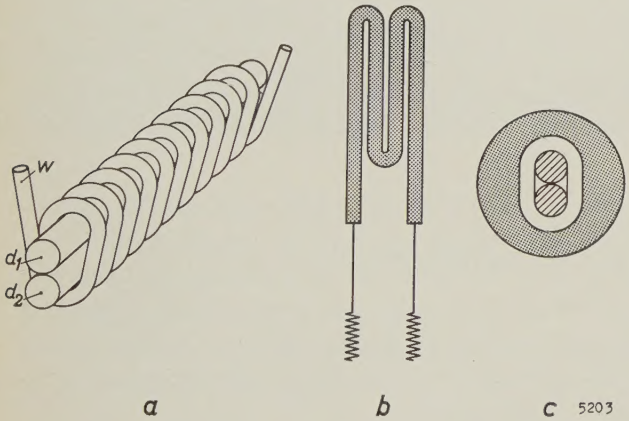

Fig. 6. Heater of half-watt cathode ($V_f = 6.3$ V).
a) Tungsten wire *w* of 30 μ is wound on a double mandrel d_1-d_2 of molybdenum wire.
b) The coiled mandrel is then bent into the shape of an M and the tungsten coil is coated with aluminium oxide.
c) Cross-section of mandrel with coil and insulation.
The mandrel is dissolved in strong acid, leaving behind the insulated heater. The free ends (see *b*) are left straight so as to reduce the radiating surface; their tips are coiled, however, to make them better visible for welding.

As mentioned in the introduction, the new cathode is primarily intended for tubes in transistorized apparatus. Now one advantage of transistors is that they start operating as soon as the apparatus is switched on. That can never be expected of an indirectly heated cathode, of course, but an effort can certainly be made to shorten the heating-up time. The half-watt cathode, used in a television picture tube, takes 8 seconds to reach 10% emission — sufficient for the picture to appear on the screen — and 13 seconds to reach 80% emission. The present 2-W cathode takes more than three times as long to reach these emission values.

The permissible voltage V_{kf} between the heater (*f*) and the cathode (*k*) is 50 V (*k* negative) or 100 V (*k* positive)[4]. If a higher V_{kf} is required for other applications, thicker insulation will of course be needed between cathode and heater, which will entail a larger emissive surface. The heater power will then have to be somewhat higher, though it will still be less than 1 W.

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[4] For the influence of polarity on the insulation between cathode and heater, see Philips tech. Rev. **18**, 188, 1956/57.

Summary of I and II. The permissible current density of conventional oxide-coated cathodes is limited by the resistance of the oxide coating and by interface resistance to 0.5-1 A/cm². Recognition of the fact that the oxide coating has two distinct functions, i.e. to emit electrons and to keep the emissive surface supplied with barium, has led to designs in which these two functions are separated. On these lines two new types of oxide-coated cathodes have been evolved: the storage cathode and the double-coated cathode, for loads of 1.5-2 A/cm² and 1-1.5 A/cm² respectively. The first type can have a life of over 5000 hours at a load of 1.5 A/cm², the second 1200-1500 hours at 1.5 A/cm² and 2000-2500 hours at 1 A/cm.

In battery-fed transistorized equipment containing a cathode-ray tube (portable television receivers, television cameras, oscilloscopes) there is a need for a C.R.T. cathode that will consume very little power, e.g. 0.5 W. Factors of importance in the design of such cathodes are the effect of heater-voltage variations on the cathode temperature, the ability to withstand shocks and vibrations, the insulation between heater, cathode and Wehnelt cylinder, and the heating-up time. The effect of heater-voltage variations can be minimized by reducing the heat loss of the cathode by conduction in favour of that by radiation. An indirectly heated oxide-coated cathode is described for 6.3 V and 86 mA (0.54 W). The standard deviation of the cathode temperature is only 10 °C. A picture tube fitted with this cathode gives a visible picture only 8 seconds after switching on. The cathode is used in oscilloscope tubes of type DH 7-11 and in vidicons of type 55 850.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS BY THE STAFF OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

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2830: A. Verloop, G. J. B. Corts and E. Havinga: Studies on vitamin D and related compounds, X. Preparation and properties of cis-isotachysterol$_2$ (Rec. Trav. chim. Pays-Bas **79**, 164-178, 1960, No. 2).

The photochemical conversion of isotachysterol$_2$ (in ether) has been studied; the effects of wavelength and time of irradiation on the composition of the irradiation mixture are discussed. On chromatography of the crude irradiation product a compound was obtained in a pure, non-crystalline form. The compound did not show antirachitic activity. The ultra-violet and infra-red absorption spectra, the iodine-catalysed quantitative conversion to isotachysterol$_2$, the behaviour on heating in solution and the very low reactivity towards maleic anhydride led to the conclusion that the compound is the Δ6,7-cis isomer of isotachysterol$_2$, i.e. 9,10-secoergosta-5(10),6-cis,8(14),22-tetraen-3β-ol.

2831: B. Bölger, B. J. Robinson and J. Ubbink: Some characteristics of a maser at 1420 MHz (Physica **26**, 1-18, 1960, No. 1).

Description of the construction of a solid-state maser (a microwave amplifier that operates by stimulated emission) for a frequency of 1420 Mc/s, i.e. the frequency of the line radiation from interstellar hydrogen. The operative ions are Cr^{3+} ions on Co sites in $K_3Co(CN)_6$, which possess four energy levels. The Cr^{3+} concentration is 0.05%. Using the pump frequency f_{13} of 3850 Mc/s, the populations n_1 and n_3 of levels *1* and *3* are equalized. When, in consequence of this, the population n_2 of the intermediate level *2* becomes greater than n_1, radiation of frequency f_{12} (the signal frequency) will give rise to stimulated emission and be amplified. The energy-level differences are adjusted to the required values (f_{12} must be 1420 Mc/s) with a variable external magnetic field. The article also describes resonance experiments designed to determine the possible adjustments of the magnetic field, the amplification and bandwidth obtained, and the behaviour of the maser at saturation. Some results achieved with ruby (Cr^{3+} in Al_2O_3) are mentioned. This particular maser is not very satisfactory for radio-astronomical measurements because of its narrow bandwidth and poor stability. Better results could be obtained by placing the emissive crystal in a slow-wave structure.

2832: N. W. H. Addink: The determination of trace elements (J. Iron and Steel Inst. **194**, 199-211, 1960, No. 2).

Description of a method of spectrochemical analysis, developed by the author and used in Philips Research Laboratories at Eindhoven, which is based on complete evaporation of the material to be analysed by a DC carbon arc. The method is suitable, among other things, for investigating very small quantities of material (as little as 0.01 microgram). The author deals with various significant factors involved, in particular with the speed of evaporation and its influence on the percentage of material lost. This factor has tended to be somewhat neglected. Results are mentioned of the analysis of solutions with and without chemical pre-concentration. The method of X-ray fluorescence analysis is then discussed and compared with spectrochemical analysis, using results obtained by both methods on a number of standard steels and determinations of zinc and iron in blood. The spectrochemical method gives reasonably accurate results and requires only very little material. The method of X-ray fluorescence gives high accuracy, but calls for the use of somewhat more material.

2833: M. Avinor: Visible emission of nickel-activated CaS (J. chem. Phys. **32**, 621-622, 1960, No. 2).

It is shown that red visible emission in nickel-activated CaS, as reported by Lenard *et al.*, is not caused by the presence of nickel alone. The red emission is presumably due to associated nickel and copper centres. By itself, nickel activation causes weak green fluorescence and copper activation blue-green fluorescence.

2834: H. Koopman and J. Daams: Investigations on herbicides, III. 2,4-disubstituted 6-chloro-1,3,5-triazines (Rec. Trav. chim. Pays-Bas **79**, 83-89, 1960, No. 1).

In view of their herbicidal properties a number of 2,4-substituted 6-chloro-1,3,5-triazines was synthesized. Their herbicidal properties are briefly discussed.